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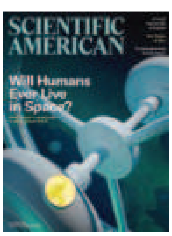
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Space enthusiasts have long predicted that humanity's future will include outposts on the moon, Mars, and other destinations. But this outcome is far from inevitable. The human body may not be able to handle life beyond Earth. The financial hurdles may be insurmountable. And murky ethical questions surround the prospect.

Illustration by Tavis Coburn.

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Why We Vax

Follow us!

Introducing Our Redesign

YOU MAY HAVE noticed we have a new logo. How do you like it? We're excited to present our redesign with the October print issue of *Scientific American*. We have new color schemes, updated graphics styles and fonts that are easy on the eyes. We've rearranged the order of our print sections to start with nuggets of news in Advances, which we follow with in-depth articles and then our columns and other departments. A new Contributors page will introduce you to some of the researchers, writers, artists, photographers and data analysts featured in each issue. It's not a radical change from our previous design, but we think it's fresh and lively and inviting. And we all love the letter C in *Scientific American*'s new logo—it's swoopy and crescent-moon-y.

Michael Mrak, our creative director, ran the redesign project with help from design firm Pentagram and a host of staff. It was a fun process. We spent hours studying mock-ups, squinting at fonts, discussing what we want to convey with our "look," making and remaking decisions, fiddling with kerning (the spacing between letters), and debating whether the short form of our name used in online platforms should be SA or SciAm. (We are going with SciAm.)

It's been a big year for us at *Scientific American*. We relaunched our daily newsletter, and people tell us they're enjoying how it delivers highlights and recommendations to their inboxes. We started a podcast series called "Science, Quickly" that is an absolute delight. (Our senior space and physics editors, Clara Moskowitz and Lee Billings, could recently be heard debating whether time travel is possible given the latest physics of wormholes and multiverses.) New episodes drop three times a week, and you can subscribe through any of the big podcast platforms. We've hired some brilliant editorial staffers to increase the number of news, commentary, graphics, multimedia and feature stories we publish online. Thank you for your support of *Scientific American* in whatever forms you enjoy our work.

In our cover story, we ask (and pretty much answer) whether humans can ever live off-planet. It's fascinating to think about all the ways our bodies and minds are adapted to life on Earth. On page 22 science journalist Sarah Scoles introduces us to "analog astronauts" who participate in mock space missions and the scientists who are looking for ways to overcome obstacles to space life. But there is no Planet B.

Several of us have had the song "Talk to the Animals" from the 1967 film *Doctor Dolittle* stuck in our heads while working on this month's story about how artificial intelligence could help us do just that. Investigative journalist Lois Parshley explains on page 44 how scientists and AIs are trying to decipher sounds from whales, birds, dogs, and more.

The history of wine has been rewritten recently, and on page 38 our senior sustainability editor Mark Fischetti and graphic artist Francesco Franchi delve into the origins and routes of grapevine evolution.

The debate over whether to use geoengineering to manage the climate crisis has quickly advanced this year, with companies already testing methods to add particles to the atmosphere to block some heat from the sun. On page 30 science writer Douglas Fox shows the stakes of this gamble and why it's being taken increasingly seriously.

Our Innovations In package of stories on environmental health equity, starting on page S1, explores opportunities for improving lives around the world with new efforts to fight air pollution, snakebites, heat islands, and more. It begins with a great conversation with Robert D. Bullard, the father of environmental justice and one of the most influential social scientists of our time.

We hope you enjoy this month's offerings and our new look.

Laura Helmuth is editor in chief of *Scientific American*. Follow her on Twitter @laurahelmuth

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TAVIS COBURN

COVER OF *SCIENTIFIC AMERICAN*

Space travel and sci-fi have always captured Tavis Coburn's imagination. A child of the 80s, he grew up on *Star Wars,* popular science magazines and comic books. Now as a digital artist based in Toronto (*self-portrait above*), he paints possible futures with the retro feel of decades past. Recently, while illustrating a new version of *The Right Stuff* (Tom Wolfe's 1979 book about the pilots who became astronauts for the U.S.'s first human spaceflight), Coburn reflected on the audacity of the first space missions. "The fact that they got those guys up in the air and back with slide rulers and compasses and math in their heads—it's a pretty astounding feat," he says. For the cover of this month's *Scientific American,* Coburn turned his eye to the future of space travel, imagining the lives of the first humans to settle down off-world. He sought to contrast advanced technology with the banal monotony of daily life. "Even though the new planet offers awe-inspiring vistas, memories of Earth flood the settlers' minds every day."

SARAH SCOLES

WHY WE'LL NEVER LIVE IN SPACE, *PAGE 22*

Would you take a one-way trip to Mars? "This used to be one of my favorite questions to liven up a dinner party," says journalist Sarah Scoles, a frequent contributor to *Scientific American,* who has written two books about the search for extraterrestrial intelligence. When Scoles was a bit younger and less risk-averse, her answer was always yes. Scoles lives in rural Colorado and enjoys "a little bit of suffering" in her outdoor adventures. But it's unlikely that Martian colonies will be seeking intrepid volunteers any time soon, she writes in this month's cover story. By immersing herself in an "analog astronaut" convention at Biosphere 2 in Arizona and speaking with experts in the field, she grappled with the massive biological, technological and political problems facing humanity's future in space. In the face of galactic optimism, she says, it's easy to forget just how big these hurdles are—and that we have "no guarantee that there's the motivation or ability to actually solve them."

FRANCESCO FRANCHI

WINE'S TRUE ORIGINS, *PAGE 38*

Graphics designer and journalist Francesco Franchi occasionally drinks wine—but only the good stuff. He's more interested in cycling the hills around Milan, Italy, where he lives. The story of the grapes we turn into wine stretches back across the entirety of human history, so Franchi's first task for devising a graphic on their 200,000-year, continent-spanning evolution was to connect time and space on the page, he says. "What I like most is to try to develop stories merging different languages," using precise combinations of illustration, photography, data and text, he says. "You have to show the relationship, the cause and effect."

LOIS PARSHLEY

TALKING WITH ANIMALS, *PAGE 44*

It all began with a mated pair of Sandhill Cranes nesting in the backyard. "We shared our mornings out on my deck," says Lois Parshley, an investigative journalist. One morning the cranes both began calling—"it was a startlingly loud noise"—for minutes at a time. Then they flew away and never returned. The mystery of what Parshley had witnessed launched her into a feature story about decoding animal communication. Nowadays the field is all about artificial intelligence; it's hard to find researchers who *aren't* using it, she says. As scientists collect terabytes on terabytes of whale clicks and crow caws, they're hoping that deep learning can find patterns and meaning in the sounds that human beings have always missed. "It's a huge open door," Parshley says, leading to captivating questions that may change our understanding of how animals experience the world.

"One of my favorite questions to liven up a dinner party used to be: Would you take a one-way trip to Mars?"
—Sarah Scoles

Illustration by Tavis Coburn

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May 2023

BUILDING A LIFE

I teared up after reading "Designing Life," in which Philip Ball exquisitely describes how the undifferentiated cells of the early embryo create differentiated tissues, organs and a body, using a genome that does not contain design-plan instructions. The interplay of chemical, physical and electrical signals in the cells and their cooperative response are astounding.
WENDY ROSENBLUM *STAMFORD, CONN.*

As I read of the multiplicity of projects experimenting with living tissues in Ball's article, I realized that this is the complementary situation to that of engineers "playing around" with artificial intelligence. Both groups have little idea of what will emerge from their activities and how it will affect the rest of us.
ARNOLD BANNER *VIA E-MAIL*

PERSECUTION PARALLELS

"Witch Hunts," by Silvia Federici and Alice Markham-Cantor, is a brilliant history of this horrifying and continuing assault against mostly women that often accompanies economic upheaval. The Supreme Court's decision to overturn the national right to an abortion has released what amounts to another contemporary "witch hunt" that targets women who seek this procedure and the medical practitioners who perform it. In many states, these women and professionals are subject to arrest and, for the latter, disbarment from their medical profession. Women travel to other states for an abortion, and those who help them are also subject to arrest.

I wish the authors had included this present outrage in their article. Considering the current amount of gun violence, I suspect this country will soon see more murders of women who want to or do have an abortion and of professionals who perform the procedure.
JIM BOTTA *DELMAR, N.Y.*

Some of the causative factors at play in centuries of accusations of female witchcraft include economic hardship and dislocation, the need for an alien scapegoat, or "other," and a strongly patriarchal social structure. While I was reading Federici and Markham-Cantor's analysis, it occurred to me that these factors may have further contemporary analogues in such accusations as "pizzagate," the conspiracy theory that falsely claimed Hillary Clinton and other high-ranking Democrats operated a secret child-sex-trafficking ring.

Most of the triggers for this kind of charge appear to be present in pizzagate: There is widespread conspiratorial rumormongering. There are threatened white males, who are often economically marginalized and facing alleged "replacement" by nonwhite people, as well as demotion from favored patriarchal hegemony by feminism and increased influence of women in politics and business. And there is even a quasireligious element with the false claim that Clinton and her acolytes performed "Satanism."

I think that many similar modern indictments of what amounts to female witchcraft could easily be found.
GERALD A. DONALDSON *SOUTHPORT, N.C.*

SOLVENT SECURITY

"Social Security and Science," by Naomi Oreskes [Observatory], asserts that "Social Security isn't a drain on the federal budget; it pays for itself through a dedicated payroll tax." The article is in error. Social Security tax receipts are already less than payments. The last Social Security Trustees report shows that demographics will cause growing problems. Lower birthrates mean there are fewer and fewer taxpayers for each recipient. There were 4.1 taxpayers per recipient in 1963, but there are only 2.7 now and expectations of just 2.3 by 2035.
ROBERT RAY *IRVINE, CALIF.*

Politicians can lie by speaking the truth in a way that misleads. They've told us Social Security (SS) benefits will need to be cut by 2034 because the SS trust funds will reach a dangerous low. They claim it's a difficult problem.

If nothing changes in the SS program, its reserves will be depleted by 2034. But raising the annual wage-base increase by a small amount would fix that. Who benefits by not solving this problem? People earning much more than the SS wage cap.
EMANUEL V. POLIZZI *MACUNGIE, PA.*

ORESKES REPLIES: *In my column, I did not say that all was well with the U.S. Social Security system. As several letter writers noted, demographic changes demand adjustments to the system. My point was that the required changes are not dramatic, but some people are exaggerating them because their antigovernment ideology leads them to look for an excuse to dismantle an extremely effective program.*

Ray is right that the numbers look large, and when taken out of context, they are frightening. But as any modeler or manager can tell you, in large systems, small changes can have large effects, especially over time. As Polizzi notes, the looming shortfall could be fixed with a small change in the wage base—the level at which workers stop paying Social Security tax on their income.

This last point highlights an odd feature

"The Supreme Court's decision to overturn the national right to an abortion has released another contemporary 'witch hunt' that targets women who seek this procedure."
JIM BOTTA *DELMAR, N.Y.*

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of the system. Most of our taxes keep increasing as our income increases. But with Social Security, payments top out at a certain amount. Right now that level is $160,200. According to a 2016 Wall Street Journal analysis, if you earned $161,413 in 2014, that would put you in the top 3 percent that year. Raising the wage base would not only close the shortfall but also make the system more equitable: currently anyone making more than $160,200 a year pays less of their income, as a percentage, in payroll taxes than someone making less than that. Another option would be to raise the retirement age, something that has been done once and could be done again.

APPROVED FOR TRANSPORT

I was delighted to read "Let's Take the Bus," Kendra Pierre-Louis's article supporting public transport as a way to help solve the climate crisis. I vacation every summer in a remote region of Italy called Val Pusteria. Moving around there used to be a nightmare until I substituted my rental car for the increasingly efficient local transport system that seamlessly coordinates the arrivals and departures of trains and buses down to the smallest of towns. It even connects to skiing venues accessible only through gondolas. Whether the U.S. can similarly deliver the punctuality, efficiency, cleanliness and safety of this region's transport system remains to be seen.

IRA SOHN *NEW YORK CITY*

CLARIFICATION

"Parrot Invasions," by Ryan F. Mandelbaum [July/August], introduced the Carolina Parakeet by saying that "North America once had its own parrot." This extinct species was specifically native to the eastern U.S.

ERRATA

"Urine Luck," by Elise Cutts [Advances; April], misspelled the family name of archaeologist Justin Pargeter.

"Science in Images," by Jordan Kinard [Advances; July/August], should have described the FlyLight initiative researchers as at the Howard Hughes Medical Institute's (HHMI's) Janelia Research Campus in Ashburn, Va., not HHMI in New York.

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ASTROPHYSICS

Out with a Bang

A nearby supernova gives stunning details of a dying star's last days



International Gemini Observatory/NOIRLab/NSF/AURA

EVERY 10 SECONDS, somewhere in the universe, a star explodes. These cataclysms spew the radiation, dust and gas that help to sculpt galaxies, form new stars and planets, and enrich the universe with heavy elements. The light from a minuscule fraction of these supernovae reaches Earth to be pored over by astronomers. Most such events are so distant that scientists have only a handful of photons to use in their attempts to learn more.

Earlier this year, however, astronomers spotted a supernova erupting a mere 21 million light-years away—a stone's throw compared with the vastness of the observable universe and one of the closest to Earth seen in a decade. Thanks to this proximity, astronomers are now piecing together its final days in lavish detail and gaining fresh insights into how these astrophysical spectacles unfold and shape the cosmos at large.

Japanese amateur astronomer Koichi Itagaki was the first to spot this supernova, known as SN 2023ixf, on May 19. Professional observers sprang into action. "The whole supernova community got on it as soon as they could," says Griffin Hosseinzadeh of the University of Arizona. The astronomers used facilities that included the Hubble Space Telescope, the International Gemini Observatory in Hawaii and the Lick Observatory in California.

Itagaki had seemingly seen the supernova erupting within the Pinwheel Galaxy, also called M101—an initial assessment that follow-up observations confirmed. From there astrophysicists wanted to identify the individual star that exploded—a difficult thing to determine with supernovae. Thankfully, Joanne Pledger of the University of Central Lancashire in England had studied the galaxy in the early 2010s using new and archival images from the Hubble Space Telescope. By zooming in on those archival images, Pledger managed to identify the exact star that had exploded.

The star was a red supergiant about 420 times the radius and about 10 times the mass of our sun. It had undergone a so-called type II supernova, in which a massive star exhausts its nuclear fuel, collapses in on itself and explosively ejects its outer layers after they bounce off its durable core, leaving behind a neutron star or a black hole. Red supergiants can grow puffy late in life and blow off shells of gas and dust from their outer atmosphere before they explode. When the supernova even-

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ADVANCES



tually erupts, it expands outward and crashes into those lingering shells, producing a discernible shock wave, which teams of astronomers detected coming from 2023ixf. "It's not the first time we've seen this happen," Hosseinzadeh says. "But the detail has never been this good."

From those observations, Wynn Jacobson-Galán of the University of California, Berkeley, and his colleagues calculated that the star lost almost 1 percent of its mass in the years before the explosion. That's actually "more than we would expect from a red supergiant star," Jacobson-Galán says. "It points, maybe, to our ignorance about how red supergiants evolve and die in the last few years before [their] explosion."

Red supergiants' dying days are crucial for understanding how supernovae enrich galaxies. How these stars lose mass "has a big influence on how galaxies evolve," says Azalee Bostroem of the University of Arizona, who has co-authored multiple studies of 2023ixf. "And it's telling us a little bit about which stars explode as which type of supernovae." Researchers also want to know where the bright burst of energy seen during a supernova comes from—whether it's entirely from the explosion or partly from the impact of the supernova shock wave on the surrounding debris. "All these things are linked with how much

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material is left on the star when it explodes," Bostroem says.

Supernova 2023ixf has also given astrophysicists their earliest-ever detailed glimpse of the intricate interactions between a supernova's shock wave and the material the star had previously shed. Specifically, scientists had debated whether the ejected gas and dust would form a sphere or some more asymmetrical shape—such as a flattened disk—around the star. The results for 2023ixf suggest the latter, says Sergiy Vasylyev of U.C. Berkeley. The exploding star's ejecta then expands in an hourglass shape as it impacts this disk. The varied orientations of debris disks with respect to their exploding host star suggest a surprising number of ways that type II supernovae can evolve. "It tells you that these events are diverse," Vasylyev says.

The nearby supernova could also help scientists predict when other red supergiants will explode. Before 2023ixf went supernova, it had been pulsating. Monika Soraisam of the National Science Foundation's National Optical-Infrared Astronomy Research Laboratory and her colleagues showed that the star had substantially swelled and shrunk in size over a period of about 1,000 days before bursting. Red supergiants are known to pulsate in this way in the denouement of their life; take Betelgeuse, a red supergiant in the constellation Orion, which has been flickering dramatically in recent years.

Astrophysicists consider these fluctuations to be a murky omen of an eventual explosion, but theoretically a star's pulsa-

ANIMAL BEHAVIOR

A Hell of a Meal

Why giant salamanders just keep eating their young


An eastern hellbender swims in the Hiwassee River in Tennessee.

Pete Oxford/Minden Pictures

MALE HELLBENDER SALAMANDERS usually make doting dads, guarding eggs and shaking them free of silt. But in some troubled populations, they are cannibalizing their entire brood every year, further jeopardizing the vulnerable giant salamander species.

Eastern hellbenders once swam in at least 570 streams in the eastern and central U.S., says Bill Hopkins, an ecologist at Virginia Tech. But numbers of the craggy, beady-eyed amphibians have plummeted in recent decades, with only about 126 streams now harboring healthy populations—and scientists didn't know why.

To solve the mystery, Hopkins's team placed hundreds of concrete nest boxes in streams in southwestern Virginia. For eight years they snooped on 182 nests, checking them every few days during the breeding season. In 60 percent of those nests not a single larva survived, most commonly because of whole-clutch cannibalism: the male had gobbled up hundreds of eggs. These cannibal dads had bulging bellies and a tendency to regurgitate the eggs when handled, the team reported in the *American Naturalist*.

The researchers' documentation of egg survival rates across time is "incredibly impressive," says Hope Klug, a behavioral ecologist at the University of Tennessee at Chattanooga, who wasn't part of the study. Cannibalism of offspring isn't unusual among animals, Klug says, explaining that parents may nutritionally benefit from consuming some offspring that they suspect won't survive. And desperately hungry parents in some species may eat their young during lean times, banking on reproducing later. Changes to the hellbenders' environment may have turned this once beneficial adaptation into a harmful evolutionary trap, Klug says.

Deforestation of the salamanders' woodland habitat may be to blame, the study findings suggest. Whole-clutch cannibalism was three times more common in areas with low upstream forest cover than in those with greater coverage. Vegetation helps to prevent streambank erosion, keeping back salt-filled silt that changes the water chemistry and fills the gaps between gravel—where hellbender larvae live. Trees also shade the streams, keeping the water cooler and more oxygen-rich.

Cannibalism isn't the only human-influenced cause of death threatening hellbender populations; anglers sometimes snag adults, and a silt-filled habitat itself can harm larvae. "This is a species that's been around for millions of years," surviving the extinction event that wiped out the dinosaurs, Hopkins says. "And now we humans are driving it to extinction."

Restoring forest cover and putting in protections around streams will take decades, Hopkins says. In the short term, conservationists could keep the numbers up by rearing hellbender larvae for release and avoiding this danger at the nest.

—Carolyn Wilke

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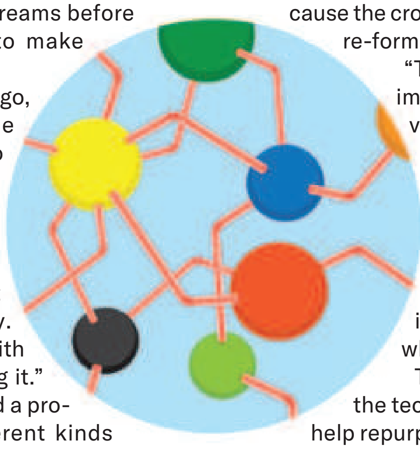
tions should have nothing to do with its going supernova. The two phenomena are caused by "totally different" mechanisms, Soraisam says. Yet such instabilities remain poorly understood, leaving the possibility that there may indeed be some kind of link. "That's the intriguing thing about 2023ixf," Soraisam says. "Very close to the explosion, we are still seeing very regular variability." If scientists can determine a link between the size shifts and the explosion, it could help them predict when other red supergiant stars will explode.

Short of seeing a supernova in our own galaxy—every modern astronomer's dream—this bright, brief spectacle in the Pinwheel Galaxy may be the best opportunity for many years to come to test current models for type II supernovae and to better see the creative destruction unleashed on the cosmos. "This is being studied in such detail and with such precision," Jacobson-Galán says. "It really is going to be one of the best-studied supernovae of the 21st century."

—*Jonathan O'Callaghan*

Linked Up A new process recycles mixed plastics

PLASTICS Soda bottles, sour cream containers and disposable cutlery—these plastics (and many others) typically arrive at recycling plants mixed together in the same bin. But because they are made of different molecular building blocks, called monomers, they must be sorted into different streams before they can be melted to make new products.



"Until about a year ago, everybody thought the only thing you could do is take a plastic, break it back down to a monomer and then re-form it," says Sanat Kumar, a chemical engineer at Columbia University. "Now we've come up with a different way of doing it." His team has developed a process that allows different kinds of plastic to be recycled together. Their findings, reported recently in *Nature*, could give new life to many items that end up in landfills.

A disturbingly small portion of our plastic waste is recycled, and production of new plastic—made from fossil fuels—continues to increase. The worsening situation has prompted scientists to seek new solutions to old recycling problems, including the difficulty of recycling mixed plastics. But they have faced a fundamental chemical hurdle: when different plastics are melted together, their various monomers tend to separate from one another like oil and water.

The new process solves this problem by adding chemicals called universal dynamic cross-linkers to the mix. Just as soap brings together oil and water, these cross-linkers (when applied under heat) form covalent molecular bonds that tether the diverse monomers together. This process creates polymers that can retain certain useful properties of each constituent plastic, such as keeping oxygen or ultraviolet light from passing through. These materials can then be melted and remade again and again because the cross-linkers can break and re-form their bonds.

"This chemistry is a really important step," says University of Washington chemical engineer Julie Rorrer, who works on plastics recycling and was not a part of the study. "They're demonstrating that this was industrially processable, which is very exciting."

The researchers hope the technique could eventually help repurpose more plastic waste, and Kumar says the process consumes less energy than breaking plastics down into their original monomers—but it's not yet cheap enough to be widely used at existing recycling facilities. Still, showing that it works could lead to lucrative markets for less expensive recycled plastics, which Kumar says would be one way to help recyclers eventually address the plastic waste crisis. "The plastics problem is huge," he says, "and you're going to have to look for multiple solutions."

—*Susan Cosier*

Illustrations by Thomas Fuchs

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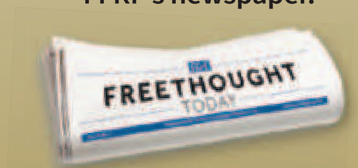


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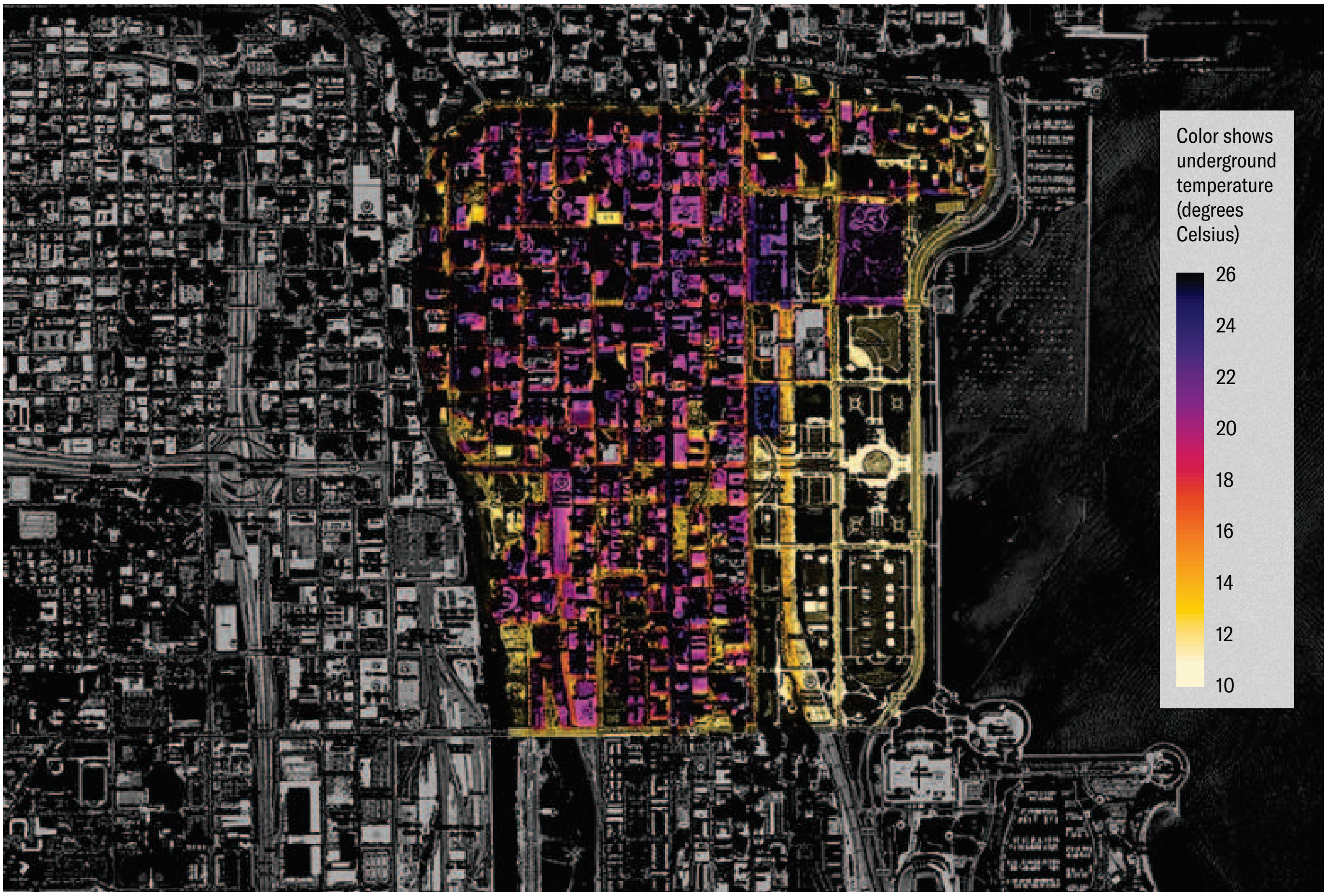


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Colors show underground temperatures in Chicago's Loop district.

CLIMATE CHANGE

Weather Underground

Warming underneath cities is weakening buildings in slow motion

CITY STREETS, SIDEWALKS and roofs all absorb heat, making some urban zones up to six degrees Fahrenheit hotter than rural ones during the day—and 22 degrees F hotter at night. These "urban heat islands" can creep underground as city heat diffuses downward, and basements, subway tunnels and other subterranean infrastructure also constantly radiate warmth into the surrounding earth. That underground heat is building up as the planet warms.

A new study of downtown Chicago shows how underground hotspots may threaten the very same structures that emit the heat in the first place: the temperature changes can make the ground expand and contract enough to cause damage. "Without [anyone] realizing it, the city of Chicago's downtown was deforming," says study author Alessandro F. Rotta Loria, a civil and environmental engineer at Northwestern University.

The findings expose a "silent hazard" for civil infrastructure in cities with softer ground—especially those near water—Rotta Loria says. "There might have been structural issues caused by this underground climate change that happened, and we didn't even realize it," he adds. Although it's not an immediate danger to human lives, this previously unknown effect shows the impacts of a lesser-known component of climate change. The findings were published in *Communications Engineering*.

Humans aren't the only ones potentially affected. "For a lot of things in the subsurface, it's kind of 'out of sight, out of mind,'" says Grant Ferguson, an engineering geologist at the University of Saskatchewan, who wasn't involved in the new study. But the underground world teems with living things that have adapted to subterranean existence, such as worms, snails, insects, crustaceans and salamanders. These creatures are used to "very static conditions," says Peter Bayer, a geoscientist at Germany's Martin Luther University Halle-Wittenberg, who was also not involved in the new study. Aboveground temperatures often swing wildly throughout the year, but the subsurface should naturally hover around the local annual average, he explains. In Chicago, that's about 52 degrees F.

The subsurface has "a memory that air temperatures don't have," Ferguson says. As these once stable temperatures rise because of climate change and urban devel-

Alessandro F. Rotta Loria (*temperature data*); OpenStreetMap (*base map*) (CC BY-SA 2.0)

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> “We could basically turn everything off, and the temperature signal will persist.”
> —Grant Ferguson
> *University of Saskatchewan*

opment, scientists such as Ferguson and Bayer are keeping tabs on the potential implications for underground ecosystems. For example, if groundwater gets too warm it could kill or drive away animals, trigger chemical changes in the water and become a breeding ground for microbes.

But the question of how underground hotspots could affect infrastructure has gone largely unstudied. Because materials expand and contract with temperature changes, Rotta Loria suspected that heat seeping from basements and tunnels could be contributing to wear and tear on various structures.

He collected three years’ worth of temperature data from more than 150 sensors installed in basements, train tunnels and parking garages below Chicago’s downtown Loop district. For comparison, sensors were also installed under Grant Park, which is located in a part of the Loop next to Lake Michigan.

The study found that Chicago’s overall ground temperatures are rising by 0.25 degree F each year, with readings in specific underground locations as much as 27 degrees F hotter than undisturbed ground. To understand how this difference has affected the ground’s physical properties, Rotta Loria used a computer model to simulate the underground environment from the 1950s to now—and then to predict how conditions will change from now until 2051.

He found that by the middle of this century some areas under the Loop may heave upward by as much as 0.50 inch or settle by as much as 0.32 inch, depending on the soil makeup of the area involved. These displacements might sound small, but Rotta Loria says they could crack the foundations and walls of some buildings. This could lead to water damage or cause buildings to tilt. In recent decades this hidden factor might have contributed to some of the continuing challenges and costs of maintaining these structures, he says.

Kathrin Menberg, a geoscientist at the Karlsruhe Institute of Technology in Germany, who was not involved in Rotta Loria’s study, says these displacement predictions are orders of magnitude higher than what she would have guessed and could be linked to Chicago’s soft, clay-heavy soils. “Clay material is particularly sensitive,” she says. “It would be a big issue in all cities worldwide that are built on such material.” This would include many cities near oceans and rivers; London, for example, sits on a layer of clay. Cities built largely on harder rock (such as New York City) would not be as strongly affected, Ferguson says.

Like climate change above the surface, underground changes occur gradually. “These effects took decades, a century, to develop,” Ferguson says, adding that elevated underground temperatures would likewise take a long time to dissipate on their own: “We could basically turn everything off, and it’s going to persist there, the temperature signal, for quite a while.”

But Ferguson and other researchers say this wasted heat energy could also be harnessed, presenting an opportunity to both cool the subsurface and save on energy costs. Subway tunnels and basements could be retrofitted with geothermal technologies to recapture the heat. For example, water pipes could be installed through underground hotspots to pick up some of the thermal energy. Although that energy wouldn’t be enough to turn the water into steam and create electricity, it could still be used to heat buildings and other civil infrastructure. This approach would require a high up-front cost and would meet only a portion of local energy demand, Menberg says.

Still, the calculus could be altered as aboveground climate change continues to amplify underground warming. In a hotter world, buildings will require more electricity to stay cool—generating more wasted energy in the form of heat. Slow as it may be, this heat will continue to accumulate under our feet. “It’s like climate change,” Rotta Loria says. “It’s happening. Maybe we don’t see it always, but it’s happening.”

—Allison Parshall

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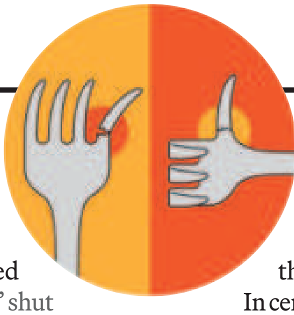
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ENGINEERING

Totally Metal

Solid metal can heal itself, researchers discover

THE CONCEPT OF self-healing metals—bridges, spaceships or robots that can spontaneously repair themselves—may be a bit closer to reality. For the first time, scientists have observed solid metal mending its own cracks without human intervention, defying fundamental theories of materials science.

"We would never think of metal as being able to self-heal cracks," says Stanford University chemical engineer Zhenan Bao, who was not involved in the new study. According to conventional materials theory, applying stress to cracked metal should only expand those cracks. The new findings "will certainly make people rethink how we predict the mechanical reliability of metal structures and equipment," Bao says.

Michael Demkowicz, a materials scientist at Texas A&M University and co-author of the new study, recently published in *Nature,* first theorized about self-healing metals 10 years ago when his computer simulations showed that solid metals could "weld" shut small cracks on their own. Because metal typically requires high temperatures to shift its form, many scientists believed the simulations were flawed, Demkowicz says.

"I thought it was a cute toy model but something very difficult to experimentally explore at the time," says study co-author Khalid Hattar, a nuclear engineer at the University of Tennessee, Knoxville. But then he stumbled on real-world evidence of Demkowicz's theory. In 2016 he and scientists at Sandia National Laboratories were studying how cracks spread across nanoscale pieces of platinum in a vacuum. They used a specialized electron microscope to prod the metal 200 times per second and watched as fractures spiderwebbed across its surface. Then, after about 40 minutes, the damage started to disappear; the researchers saw the fissures fuse back together as if in a video played in reverse. "I guess Mike was right after all," Hattar remembers thinking.

The self-healing ability appears to arise when the edges of a crack are pressed close enough together for their respective atoms to bond. In certain "sweet spot" areas, irregularities in a metal's neat, crystalline structure shift when external tension—such as the force exerted by natural wear and tear—is applied. As these irregularities move, they induce a compressive stress that triggers the rebonding effect.

The Sandia team and Demkowicz replicated their observations with both platinum and copper. Computer simulations suggest that aluminum and silver should also self-heal, but the researchers don't know whether alloys such as steel can perform this feat. It's also unclear whether self-healing could ever be a practical tool outside a vacuum; atmospheric particles inside a crack may prevent it from fusing back together, the team says. Still, this phenomenon will cause some materials scientists to rethink what they know about metal. "Under the right circumstances," Demkowicz says, "materials can do things we never expected." —*Lucy Tu*

Ancient Antimicrobials

You kill more bacteria with honey and vinegar than with either alone

MEDICINE

Honey and vinegar, a traditional medicinal combination known as oxymel, dates to the ancient world. Apothecaries in the Middle Ages sold it, Hippocrates prescribed it and the physician-philosopher Ibn-Sīnā extolled its virtues. Today such a mixture sounds likelier to dress a salad than a lesion—but with antibiotic-resistant bacteria on the rise, scientists are eagerly seeking new ways to fight intransigent infections. Now a study in *Microbiology* suggests oxymel may indeed help.

"In modern medicine both honey and acetic acid are used individually to treat infected wounds," but they are typically not combined, says study co-author Erin Connelly, an interdisciplinary researcher at the University of Warwick in England, who studies the antimicrobial properties of historic remedies. Honey stresses bacteria and fights infections with its high sugar content and acidity. Similarly, vinegar's active component, acetic acid, is a natural antiseptic that breaks down bacterial DNA and proteins.

Neither compound is particularly effective alone, Connelly and her team found. The researchers applied low doses of honey and acetic acid separately to laboratory-grown formations called biofilms, made up of the common wound pathogens *Pseudomonas aeruginosa* and *Staphylococcus aureus.* Most of the bacteria lived. "But when we put these low doses together, we saw a large number of bacteria dying, which is really exciting," says study co-author Freya Harrison, who studies chronic infections at the University of Warwick. Oxymel killed up to 1,000 times more bacteria in the biofilm than vinegar alone and up to 100,000 times more than honey alone.

Oxymel could be particularly valuable for chronic wound infections, the researchers say. These long-lived skin lesions are common in people with diabetes or burn trauma, and they often contain organized colonies of stubbornly antibiotic-resistant bacteria. It is estimated that 1 to 2 percent of the population in developed countries will experience a chronic wound during their lifetime, and the rate appears to be increasing as diabetes becomes more common.

"Chronic wounds are a huge burden on the health-care system," says Andrew Vardanian, a plastic surgeon at UCLA Health, who specializes in complex wounds. "We need alternatives because some treatments don't work for certain patients." Additionally, long-term antibiotic use on a stubborn infection can make the bacteria more drug-resistant. Oxymel would also be much cheaper than existing infection treatments, Vardanian explains.

Next the researchers plan to investigate why the combination of honey and vinegar works better than either alone, which remains a mystery for now. If oxymel proves successful in treating humans, this inexpensive old remedy would be an important addition to the arsenal for fighting resistant infections. —*Leo DeLuca*

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Power Trips

Tough new wildlife tracker runs on animal power

CONSERVATION To study the behavior of elusive animals, scientists routinely tag them with GPS location trackers. But such devices' battery capacity limits how long they operate, often bringing an early end to vital conservation work.

Solar-powered trackers break easily, making them a poor choice for devices strapped to larger mammals—and they don't work for nocturnal creatures. So biologist Rasmus Worsøe Havmøller of the University of Copenhagen and his colleagues turned to another abundant power source: kinetic energy generated by an animal's movements. Their kinetic tracker, which Havmøller's team recently tested on domestic dogs, a wild pony and a European bison, could theoretically survive for the entire life span of an active animal. It is also lighter and cheaper to make than its battery-powered counterparts.

The design "is ingenious and exciting," says Mark Hebblewhite, a habitat ecologist at the University of Montana, who was not involved with the new work. The proof-of-concept kinetic tracker works by means of a magnetic pendulum that swings around a copper coil, generating electricity as the tagged animal moves. The dogs and bison in the study were active enough to create the energy to transmit one location ping per day for 14 days and 17 days, respectively. One of the wild pony's trackers lasted at least 146 days but didn't produce enough power for daily transmissions, the researchers reported in *PLOS ONE.*

The limited power generated by the animals' movements means the technology isn't ready for prime time just yet, says ecologist Emily Studd of British Columbia's Thompson Rivers University, who wasn't involved in the study. When researchers want to keep close tabs on animals, they often need GPS fixes more than once a day. But Studd says that "with a bit more development, this could be a game changer for wildlife animal research and monitoring."

Havmøller and his colleagues hope conservation workers can one day use this technology to track species such as tigers, leopards and wolves, which can easily destroy solar-powered trackers—and which hunt and travel at night. —*Rachel Crowell*



M. K. Ranjitsinh/Science Source

The researchers tested the new tracker on a European bison.

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MATERIALS SCIENCE

Fireproof Fungi

Mycelium sheets could keep buildings from burning



The fireproof material was made from the mycelium of Southern Bracket fungus.

Bob Gibbons/Minden Pictures

IN A WORLD where fire threatens more and more homes, scientists have developed a surprising type of material that might keep some buildings safer: wafer-thin sheets of fungi.

Underneath every mushroom is a sprawling, branching network of rootlike structures called a mycelium. Now researchers have successfully grown these networks into Pop Tart–size sheets that could act as a fire retardant in building materials, according to a new study in *Polymer Degradation and Stability*.

Using a biological material like mycelium has enormous benefits, says senior author Everson Kandare. Unlike asbestos, which is still sometimes added to building materials as a fire retardant, mycelium does not shed noxious compounds when exposed to fire. "When there is a building fire, it [often] isn't the flame intensity or the heat that kills or injures people," says Kandare, an engineer at RMIT University in Melbourne, Australia. "It is the fumes and the toxic metal that comes out of building materials."

The new mycelium sheets, grown into their unique shape in a plastic container and stacked into protective mats up to a few millimeters thick, could prevent such building materials from burning in the first place. Mycelium contains a lot of carbon. When exposed to fire, the sheet briefly burns, releasing water and carbon dioxide into the air, before petering out and leaving behind a black layer of carbon.

"In order for fire to spread, it has to burn. If you're left with an area you can't burn, then that stops the fire," says Chris Hobbs, a polymer chemist at Sam Houston State University in Texas, who was not involved in the new study but says he considers the material promising.

Scientists have known about mycelium's flame-retardant properties for several years, but Kandare says this study is the first to incorporate these properties into a useful building material. He suggests mycelium could replace the fire-retardant foam that insulates many commercial buildings, which can produce carbon monoxide and other toxic products when it combusts.

The RMIT team has been reaching out to mushroom farmers to see whether they could scale the technology for commercial use. Kandare is optimistic because mycelium can grow in the dark, which means its energy needs are relatively minimal—and the team fed its prototype with ordinary molasses. Even better, mycelium is a biological material, and any waste it leaves behind is compostable.

"If the product reaches the end of its life, you can just chuck that mycelium in your garden," Kandare says. "Just toss it in the green beans."

—Timmy Broderick

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Fish Eye Collagen from tilapia skin repairs corneas

HEALTH Tilapia skin is rich in collagen, and this structural protein's abundance has made the fish a popular resource in veterinary and human medicine. Researchers have explored its use in applications from bandaging burn victims and correcting abdominal hernias to mending heart valves and reconstructing vaginas.

Inspired by colleagues in a dozen other specialties, Mirza Melo, a veterinary ophthalmologist in northeastern Brazil's Ceará state, tested tilapia skin to treat a pervasive problem in her field: corneal ulcers and perforations, particularly in dogs with short snouts. "These are species with very prominent eyes," she says. "So they get injured often."

Such corneal injuries are commonly treated by surgically placing a membrane made of horse placenta (also a collagen source but with a lower concentration than tilapia skin, Melo says) over the affected area to help it regenerate. Melo first swapped that membrane for tilapia skin in 2019, when she successfully operated on a Shih Tzu with a severe corneal perforation.

Brazil's Burn Support Institute and the Federal University of Ceará—home of the Tilapia Skin Project, which pioneered the skin's use to treat burns—approached her about the surgical technique. With their support Melo began testing a membrane she called the acellular dermal matrix (ADM), made of pure collagen extracted from the fish skin.

Collagen is known to stimulate cellular growth and to "guide the generation of various tissues," Melo says. A tilapia's collagen supply and quality remain high throughout the fish's entire life, whereas horse-placenta collagen varies depending on factors such as the animal's age and weight, she says.

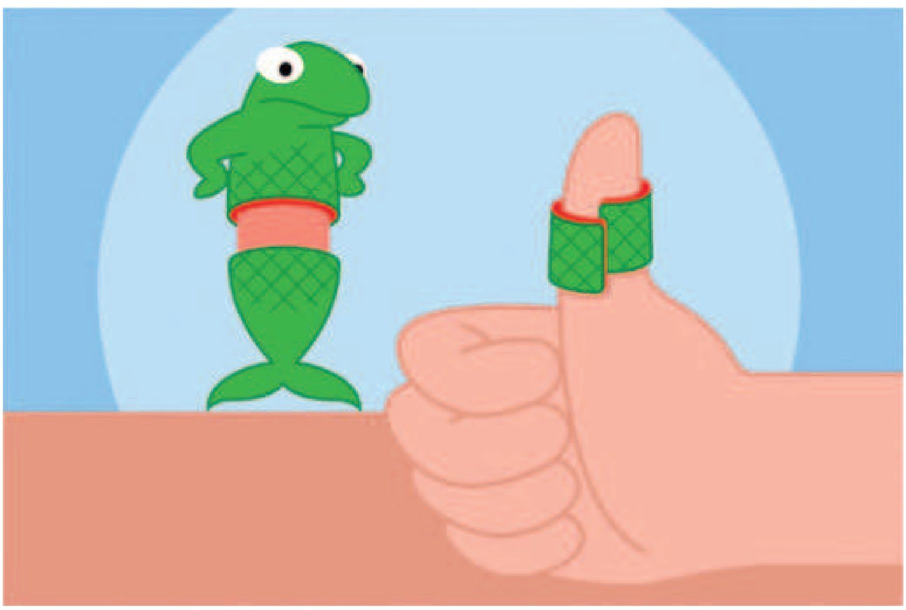
The processed ADM resembles a thick sheet of paper. Veterinarians rehydrate it with saline solution before surgery, then lay it over a dog's corneal lesion and suture it into place, where it acts as scaffolding for regenerating cells.

The 400-plus dogs Melo has treated so far have shown no pain or problems with infection after surgery. They also healed quickly, with minimal scarring that would affect postsurgical care.

Current corneal repair strategies such as using horse placenta, grafting and transplant have good results—but scarring continues to be a concern, says Robson Santos, a veterinary ophthalmologist not involved in the ADM project. "Tilapia skin is an excellent alternative to the well-established techniques we already have," he says.

Melo is now looking to use the technique on cats, and she says discussions have already begun on how to adapt it for humans. She also hopes to take her research to the eye's retina, which is particularly challenging to treat because of its extremely sensitive specialized neurons.

"It's where we have the most limited resources, in both veterinary and human ophthalmology," Melo says. "So we hope to get there one day." *—Jill Langlois*



NEWS AROUND THE WORLD

Quick Hits

By Lucy Tu

AUSTRALIA
Australia is the first country to legalize psilocybin and MDMA for the treatment of depression and post-traumatic stress disorder. As clinical trials for these and other psychedelics gain momentum worldwide, Australia could be a model for governments considering regulation of these substances as medications.

CHINA
A 125-million-year-old fossil of a badger-like animal biting a beaked dinosaur was unearthed in northeastern China. Most paleontologists thought mammals only scavenged dinosaur remains, but the find suggests early mammals hunted live dinosaurs several times their size.

GREENLAND
A mile-thick ice sheet in Greenland melted during a period of moderate warming 416,000 years ago, sediments show. This overturns long-held beliefs that the island remained an icy fortress for the past 2.5 million years, revealing its vulnerability to today's human-induced climate change.

KENYA
Construction has begun on a 35-megawatt geothermal power project in Menengai, Kenya, the top geothermal-energy-producing country in Africa. Geothermal plants provide 47 percent of Kenya's energy, and production is expected to grow as droughts reduce hydropower sources.

LAOS
Human skull and shinbone fossils found in a Laos cave suggest modern humans arrived in mainland Southeast Asia up to 36,000 years earlier than thought. This discovery challenges hypotheses that humans rapidly spread from Africa through Asia 80,000 years ago.

U.S.
Ocean temperatures off Florida spiked to a record 100 degrees Fahrenheit, causing the worst coral-bleaching event in the state's history. Conservationists say some reefs face "100 percent coral mortality," meaning the reefs won't recover without active, ongoing restoration work.

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EVOLUTION

Flight Secrets

Key genes unlocked the sky for bats

BATS HAVE DONE something no other mammal ever has: the leathery-winged beasts evolved powered flight thanks to specialized membranes called patagia connecting their limbs and digits to the rest of their body. A new study of bat embryos in *BMC Biology* reveals a crucial step in how these once land-bound animals evolved to fly—and it may involve a gene known for detrimental mutations in humans.

Paleontologists have yet to discover fossils showing a transition to the earliest flying bats. But the embryonic development of today's living bats contains clues to these ancient changes. "The bat wing is a crazy amalgam of derived and novel anatomical elements," says study author Karen Sears, a biologist at the University of California, Los Angeles. And the plagiopatagium, a specific patagium that connects the side of the body to the arms and legs, is among the most important. This tissue takes on a variety of shapes in different bat species, tending to be broader in fruit-eating species and narrower in ones that hunt flying insects. To detect whether these shapes came from an ancestral bat wing or evolved independently, Sears and her colleagues investigated the embryology of different bat species and the genes responsible for the tissue's development.

During development, the researchers found, the plagiopatagium grows from the side of the fetus's body and merges with its limbs. This pattern held across all the species studied, indicating an ancestral wing. A mutation in a particular gene called *Ripk4* may have enabled the change.

"Evolution is unpredictable, and development is often modified in ways that we cannot, or do not, anticipate," Sears says. In humans and laboratory mice, mutations to *Ripk4* can alter the skin to create patagiumlike structures and cleft lips, among other issues. About half of all living bat species have cleft palates—a feature that may be tied to bat echolocation.

The findings provide important evidence for how skin layers fuse together to form bats' essential flight membrane, says University of Melbourne biologist Charles Feigin, who was not involved in the new study. This fusion makes the wings resilient enough for powered flight, Feigin says; similar, weaker membranes in other airborne mammals limit them to gliding. A chance mutation might have been the key that opened the sky to bats. *—Riley Black*

Joint Effort A new above-elbow bionic arm can control every finger

ROBOTICS

Most bionic limbs are controlled by electrical signals generated by muscles moving near the attachment site. But when an arm is amputated above the elbow, the remaining muscles aren't enough to control every joint in an artificial hand. "The higher the amputation, the more joints you have to replace, and the fewer muscles you have to do it," says Max Ortiz Catalán, a bionicist at Chalmers University of Technology in Sweden.

Now Ortiz Catalán's team has developed a bionic system that allowed a man with an above-elbow amputation to control every finger of a robotic arm, as described recently in *Science Translational Medicine*. To create more muscle signals to prompt the prosthetic, the researchers dissected the nerve bundles that carry signals from the man's brain to muscles in his upper arm. The fibers were then spread out and attached to new muscle targets in his remaining arm, including muscle tissue grafted from his thigh. They also anchored a titanium fixture into the remaining upper-arm bone, making the prosthesis more comfortable than typical fitted socket attachments.

Prosthetics usually pick up muscle signals with electrodes on the skin's surface. For the new device, the researchers used a more reliable technique: implanting electrodes directly on or within the muscles. This commonly involves running wires through the skin—a design feasible only in laboratory settings, not in daily life. But in the new system, wires pass through the titanium bolt and into the robotic arm. A processor in the prosthesis then uses an artificial-intelligence algorithm to translate the muscle signals into control signals for joints in the arm and hand.

The man has been using the prosthesis in his daily life for more than three years to grasp objects and pour drinks. "This is the first nerve-based prosthetic hand that the patient can go home with," says bioengineer Cynthia Chestek of the University of Michigan, who was not involved in the project. The team is working to optimize the controllability of the prosthesis and to integrate sensory feedback.

Still, attaching the device requires major surgery that carries a risk of infection. "Not all amputees are going to want a titanium bolt through their skin," Chestek says. Also, the prosthesis has so far been demonstrated just once. "It's only one participant, but it shows some exciting results," says prosthetic scientist Laura Miller of the Shirley Ryan AbilityLab in Chicago. Her group is planning to collaborate with Ortiz Catalán on a larger trial. "We're excited to do this type of procedure with more people," she says.

—Simon Makin

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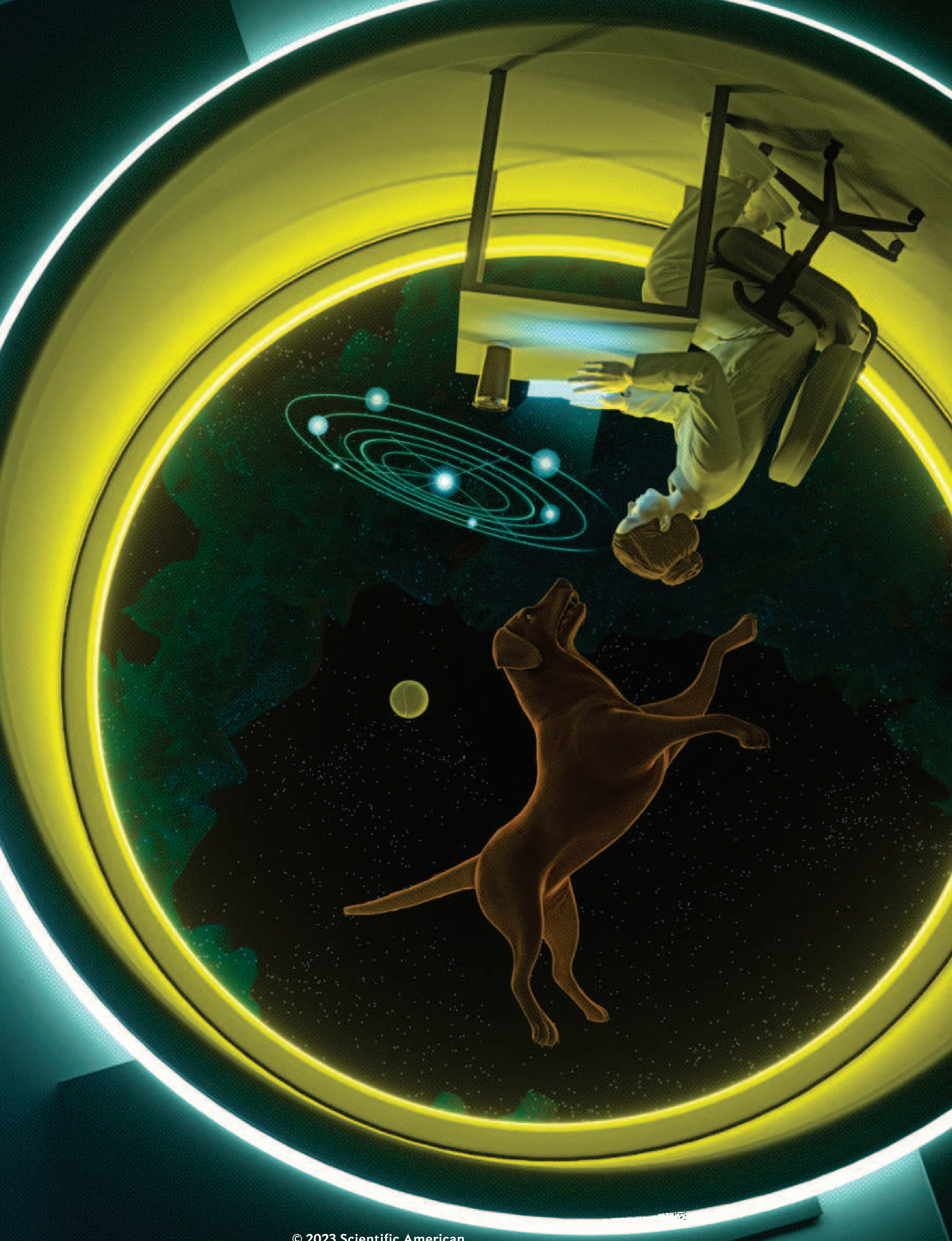
SPACE TRAVEL

WHY WE'LL NEVER LIVE IN SPACE

The technological, biological, psychological and ethical challenges to leaving Earth BY SARAH SCOLES

ILLUSTRATION BY TAVIS COBURN

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NASA WANTS ASTRONAUT boots back on the moon a few years from now, and the space agency is investing heavily in its Artemis program to make it happen. It's part of an ambitious and risky plan to establish a more permanent human presence off-world. Companies such as United Launch Alliance and Lockheed Martin are designing infrastructure for lunar habitation. Elon Musk has claimed SpaceX will colonize Mars. But are any of these plans realistic? Just how profoundly difficult would it be to live beyond Earth—especially considering that outer space seems designed to kill us?

Humans evolved for and adapted to conditions on Earth. Move us off our planet, and we start to fail—physically and psychologically. The cancer risk from cosmic rays and the problems that human bodies experience in microgravity could be deal-breakers on their own. Moreover, there may not be a viable economic case for sustaining a presence on another world. Historically, there hasn't been much public support for spending big money on it. Endeavors toward interplanetary colonization also bring up thorny ethical issues that most space optimists haven't fully grappled with.

At this year's Analog Astronaut Conference, none of these problems seemed unsolvable. Scientists and space enthusiasts were gathered at Biosphere 2, a miniature Earth near Tucson, Ariz., which researchers had built partly to simulate a space outpost. Amid this crowd, the conclusion seemed foregone: living in space is humans' destiny, an inevitable goal that we must reach toward.

The conference attendees know it's a big dream. But their general outlook was summed up by Phil Hawes, chief architect for Biosphere 2, who gave the opening talk at the meeting. He recited a toast made by the first team to camp out here decades ago: "Here's to throwing your heart out in front of you and running to catch up with it."

The question remains as to whether we can—and will—ever run fast enough.

IN 1991 EIGHT PEOPLE ENTERED BIOSPHERE 2 AND lived inside for two years. This strange facility is a 3.14-acre oasis where scientists have re-created different terrestrial environments—not unlike an overgrown botanical garden. There's an ocean, mangrove wetlands, a tropical rainforest, a savanna grassland and a fog desert, all set apart from the rest of the planet they're mimicking. One goal, alongside learning about ecology and Earth itself, was to learn about how humans might someday live in space, where they would have to create a self-contained and self-sustaining place for themselves. Biosphere 2, located on Biosphere 1 (Earth), was practice. The practice, though, didn't quite work out. The encapsulated environment didn't produce enough oxygen, water or food for the inhabitants—a set of problems that, of course, future moon or Mars dwellers could also encounter. The first mission and a second one a few years later were also disrupted by interpersonal conflicts and psychological problems among the residents.

Today the people who participate in projects like Biosphere 2—simulating some aspect of long-term space travel while remaining firmly on Earth—are called analog astronauts. And although it's a niche pursuit, it's also popular: There are analog astronaut facilities in places such as Utah, Hawaii, Texas and Antarctica. People are building or planning them in Oman, Kenya and Israel. And they all share the goal of learning how to live off Earth while on Earth.

Sarah Scoles is a Colorado-based science journalist, a contributing editor at *Popular Science*, and a senior contributor at *Undark*. She is author of *Making Contact* (2017) and *They Are Already Here* (2020), both published by Pegasus Books. Her book *Countdown: The Blinding Future of Nuclear Weapons* (Public Affairs) will be out in 2024.

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The people who are mingling on Biosphere's patio, where the desert sunset casts a pink light on the habitat's glass exterior, are part of that analog world. Some of them have participated in simulation projects or have built their own analog astronaut facilities; others are just analog-curious. They are astronomers, geologists, former military personnel, mail carriers, medical professionals, FedEx employees, musicians, artists, analysts, lawyers and the owner of the Tetris Company. On this night many have donned Star Wars costumes. As the sun goes down, they watch the rising moon, where many here would like to see humans settle.

HUMAN BODIES REALLY CAN'T handle space. Spaceflight damages DNA, changes the microbiome, disrupts circadian rhythms, impairs vision, increases the risk of cancer, causes muscle and bone loss, inhibits the immune system, weakens the heart, and shifts fluids toward the head, which may be pathological for the brain over the long term—among other things.

At the University of California, San Francisco, medical researcher Sonja Schrepfer has dug into two of the conditions that afflict space explorers. Her research, using mice floating within the International Space Station, has revealed that blood vessels leading to the brain get stiffer in microgravity. It's part of why today's astronauts can't simply walk out of their capsules once they return to Earth, and it would play out the same way on Mars—where there's no one to wheel them to their new habitat on arrival. Schrepfer and her colleagues did, however, uncover a molecular pathway that might prevent those cardiovascular changes. "But now the question I try to understand is, Do we want that?" she says. Maybe the vessels' stiffening is a protective mechanism, Schrepfer suggests, and limbering them up might cause other problems.

She also wants to figure out how to help astronauts' faltering immune systems, which look older and have a harder time repairing tissue damage than they should after spending time in space. "The immune system is aging quite fast in microgravity," Schrepfer says. She sends biological samples from young, healthy people on Earth up to orbit on tissue chips and tracks how they degrade.

Vision and bone problems are also among the more serious side effects. When astronauts spend a month or more in space, their eyeballs flatten, one aspect of a condition called spaceflight-associated neuro-ocular syndrome, which can cause long-lasting damage to eyesight. Bones and muscles are built for life on Earth, which involves the ever present pull of gravity. The work the body does against gravity to stay upright and move around keeps muscles from atrophying and stimulates bone growth. In space, without a force to push against, astronauts can experience bone loss that outpaces bone growth, and their muscles shrink. That's why they must do hours of exercise every day, using specialized equipment that helps to simulate some of the forces their anatomy would feel on the ground—and even this training doesn't fully alleviate the loss.

Perhaps the most significant concern about bodies in space, though, is radiation, something that is manageable for today's astronauts flying in low-Earth orbit but would be a bigger deal for people traveling farther and for longer. Some of it comes from the sun, which spews naked protons that can damage DNA, particularly during solar storms. "[That] could make you very, very sick and give you acute radiation syndrome," says Dorit Donoviel, a professor at the Baylor College of Medicine and director of the Translational Research Institute for Space Health (TRISH).

Future astronauts could use water—perhaps pumped into the walls of a shelter—to shield themselves from these protons. But scientists don't always know when the sun will be spitting out lots of particles. "So if, for example, astronauts are exploring the surface of the moon, and there is a solar particle event coming, we probably have the capability of predicting it within about 20 to 30 minutes max," Donoviel says. That means we need better prediction and detection—and we'd need astronauts to stay close to their H_2O shield.

Perhaps the most significant concern is radiation, something that is manageable for today's astronauts flying in low-Earth orbit but would be a bigger deal for people traveling farther and for longer.

If you didn't get to safety in time, the nausea would come first. "You would vomit into your spacesuit," Donoviel says, "which now becomes a life-threatening situation" because the vomit could interfere with life-support systems, or you might breathe it in. Then comes the depletion of cells such as neutrophils and red blood cells, meaning you can't battle germs or give your tissues oxygen effectively. You'll be tired, anemic, unable to fight infection, and throwing up. Maybe you'll die. See why lots of kids want to be astronauts when they grow up?

There's another type of radiation, galactic cosmic rays, that even a lot of water won't block. This radiation is made of fast-moving elements—mostly hydrogen but also every natural substance in the periodic table. The rays burst forth from celestial events such as supernovae and have a lot more energy and mass than a mere proton. "We really cannot fully shield astronauts" from them, Donoviel says. And inadequately

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From September 1991 to September 1993, eight people lived inside the Biosphere 2 research facility in Arizona, helping scientists learn how humans might live in outer space. The facility houses a greenhouse (*right*).

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shielding explorers makes the problem worse: the rays would split when they hit a barrier, making more, smaller particles.

The radiation an astronaut en route to Mars might get from galactic cosmic rays at any one time is a small dose. But if you're on a spaceship or a planetary surface for years, the calculus changes. Imagine, Donoviel says, being in a room with a few mosquitoes. Five or 10 minutes? Fine. Days? Months? You're in for a whole lot more itching—or, in this case, cancer risk.

Because shielding astronauts isn't realistic, Donoviel's TRISH is researching how to help the body repair radiative damage and developing chemical compounds astronauts could take to help fix DNA damage in wounds as they occur. "Everybody's worried about waiting for the cancer to happen and then killing the cancer," Donoviel says. "We're really taking the preventive approach."

Even if most of the body's issues can be fixed, the brain remains a problem. A 2021 review paper in *Clinical Neuropsychiatry* laid out the psychological risks that astronauts face on their journey, according to existing research on spacefarers and analog astronauts: poor emotional regulation, reduced resilience, increased anxiety and depression, communication problems within the team, sleep disturbances, and decreased cognitive and motor functioning brought on by stress. To imagine why these issues arise, picture yourself in a tin can with a small crew, a deadly environment outside, a monotonous schedule, an unnatural daytime-nighttime cycle and mission controllers constantly on your case.

PHYSICAL AND MENTAL HEALTH PROBLEMS—though dire—aren't even necessarily the most immediate hurdles to making a space settlement happen. The larger issue is the cost. And who's going to pay for it? Those who think a billionaire space entrepreneur is likely to fund a space colony out of a sense of adventure or altruism (or bad judgment) should think again. Commercial space companies are businesses, and businesses' goals include making money. "What is the business case?" asks Matthew Weinzierl, a professor at Harvard Business School and head of its Economics of Space research efforts.

For the past couple of years Weinzierl and his colleague Brendan Rousseau have been trying to work out what the demand is for space exploration and pursuits beyond Earth. "There's been a ton of increase in supply and cutting of costs of space activity," Weinzierl says, "but who's on the other side?" Space companies have historically been insular: specialists creating things for specialists, not marketing wares or services to the broader world. Even commercial undertakings such as SpaceX are supported mostly by government contracts. Company leaders haven't always thought through the capitalism of their ideas; they're just excited the rockets and widgets work.

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"Technical feasibility does not equal a strong business case," Rousseau says.

Today private spaceflight companies target tourists for business when they're not targeting federal contracts. But those tourists aren't protected by the same safety regulations that apply to government astronauts, and an accident could stifle the space tourism industry. Stifling, too, is the fact that only so many people with money are likely to want to live on a place like Mars rather than take a short joyride above the atmosphere, so the vacation business case for permanent space outposts breaks down there as well.

People tend to liken space exploration to expansion on Earth—pushing the frontier. But on the edge of terrestrial frontiers, people were seeking, say, gold or more farmable land. In space, explorers can't be sure of the value proposition at their destination. "So we have to be a little bit careful about thinking that it will just somehow pay off," Weinzierl points out.

Weinzierl and Rousseau find the idea of a sustained human presence in space inspiring, but they're not sure when or how it will work from a financial perspective. After all, inspiration doesn't pay invoices. "We'd love to see that happening," Rousseau says—he thinks lots of people would. "As long as we're not the ones footing the bill."

Many taxpayers would probably agree. As hard as it is for space fans to believe, most people don't place much value on astronaut adventures. A 2018 Pew poll asked participants to rate the importance of nine of NASA's key missions as "top priority," "important but lower priority," or "not too important/should not be done." Just 18 and 13 percent of people thought sending humans to Mars and to the moon, respectively, was a top priority. That placed those missions at the bottom of the list in terms of support, behind more popular efforts such as monitoring Earth's climate, watching for dangerous asteroids and doing basic scientific research on space in general.

A 2020 poll from Morning Consult found that just 7 to 8 percent of respondents thought sending humans to the moon or Mars should be a top priority. Although history tends to remember the previous moon exploration era as a time of universal excitement for human spaceflight, polls from the time demonstrate that that wasn't the case: "Consistently

On the edge of terrestrial frontiers, people were seeking, say, gold or more farmable land. In space, explorers can't be sure of the value proposition at their destination.

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throughout the 1960s, a majority of Americans did not believe Apollo was worth the cost, with the one exception to this a poll taken at the time of the *Apollo 11* lunar landing in July 1969," wrote historian Roger Launius in a paper for *Space Policy*. "And consistently throughout the decade 45–60 percent of Americans believed that the government was spending too much on space, indicative of a lack of commitment to the spaceflight agenda."

Harmful extraterrestrial microbes could return with astronauts or equipment—a planetary-protection risk called backward contamination.

When space agency officials discuss why people should care about human exploration, they often say it's for the benefit of humanity. Sometimes they cite spin-offs that make their way to citizens as terrestrial technology—such as how telescope-mirror innovations improved laser eye surgery. But that argument doesn't do it for Linda Billings, a consultant who works with NASA. If you were interested in furthering a technology, she suggests, you could invest directly in the private sector instead of obliquely through a space agency, where its development will inevitably take longer, cost more and not be automatically tailored toward earthly use. "I don't see that NASA is producing any evidence that [human settlement of space] will be for the benefit of humanity," she says.

WHETHER TAX DOLLARS SHOULD support space travel is an ethical question, at least according to Brian Patrick Green of Santa Clara University. Green became interested in science's ethical issues when he worked in the Marshall Islands as a teacher. The U.S. used to detonate nuclear weapons there, causing lasting environmental and health damage. Now the islands face the threat of sea-level rise, which is likely to inundate much of its infrastructure, erode the coasts and shrink the usable land area. "That got me very interested in the social impacts of technology and what technology does to people and societies," he says.

In space travel, "Why?" is perhaps the most important ethical question. "What's the purpose here? What are we accomplishing?" Green asks. His own answer goes something like this: "It serves the value of knowing that we can do things—if we try really hard, we can actually accomplish our goals. It brings people together." But those somewhat philosophical benefits must be weighed against much more concrete costs, such as which other projects—Earth science research, robotic missions to other planets or, you know, outfitting this planet with affordable housing—aren't happening because money is going to the moon or Mars or Alpha Centauri.

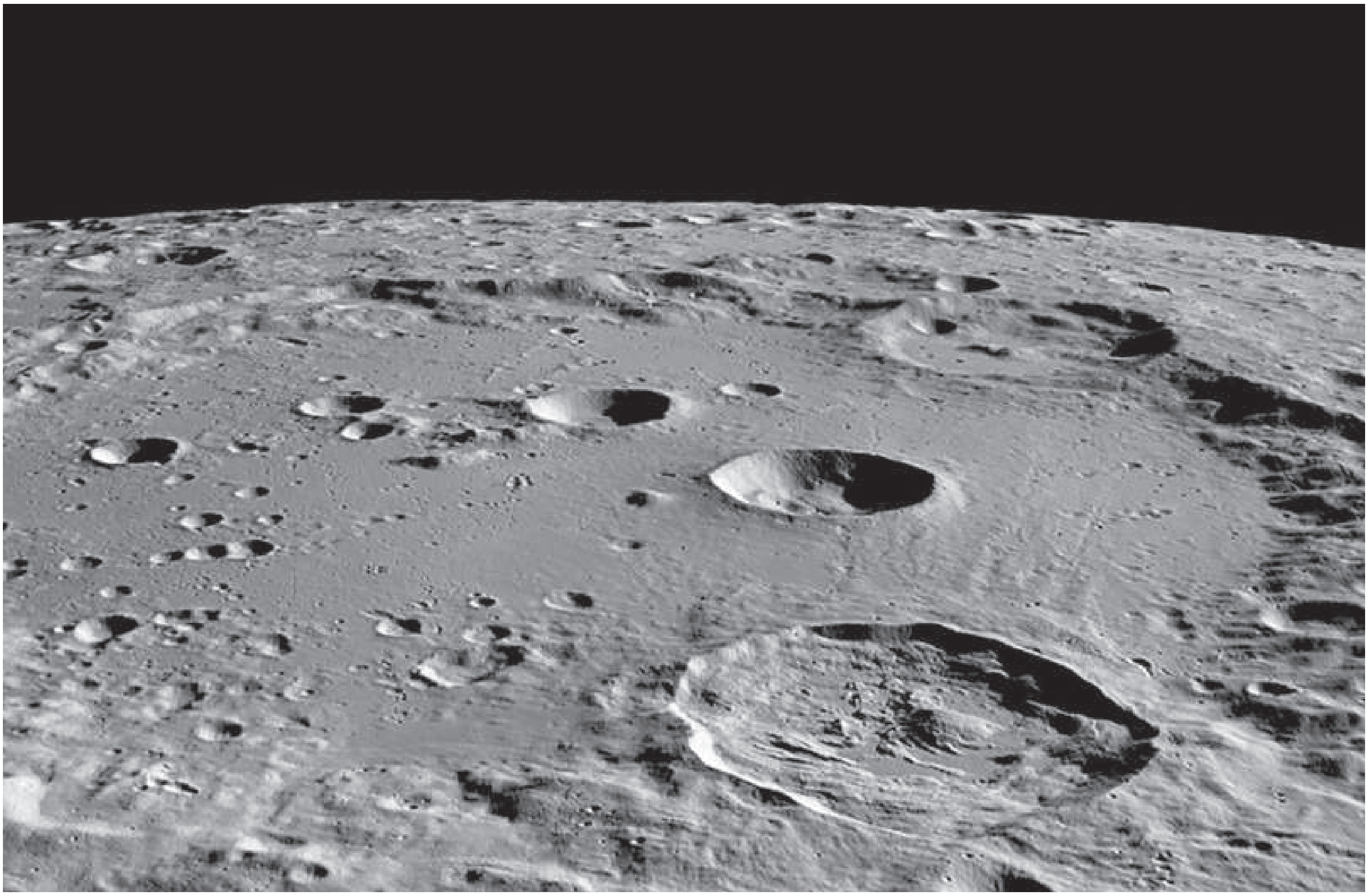
And an even simpler ethical question is, "Should we actually send people on these sorts of things?" Green says. Aside from incurring significant risks of cancer and overall body deterioration, astronauts aiming to settle another world have a sizable chance of losing their lives. Even if they do live, there are issues with what kind of an existence they might have. "It's one thing just to survive," Green says. "But it's another thing to actually enjoy your life. Is Mars going to be the equivalent of torture?"

If people make the attempt, we will also have to acknowledge the risks to *celestial* bodies—the ones humans want to travel to as well as this one, which they may return to if they haven't purchased a one-way ticket. The moon, Mars or Europa could become contaminated by microscopic Earth life, which NASA has never successfully eradicated from spacecraft, although it tries as part of a "planetary protection" program. And if destination worlds have undetected life, then harmful extraterrestrial microbes could also return with astronauts or equipment—a planetary-protection risk called backward contamination. What obligation do explorers have to keep places as they found them? Setting aside the question of whether we can establish ourselves beyond Earth, we also owe it to ourselves and the universe to consider whether we should.

ON THIS QUESTION, SCIENCE-FICTION scholar Gary Westfahl casts doubt on space travel's inherent value. In his vast analyses of sci-fi, he has come to view the logic and drive of the enterprise as faulty. "I inevitably encountered the same argument: space travel represents humanity's destiny," he says of the impetus for writing his essay "The Case against Space." Space explorers are often portrayed as braver and better than those who remain on their home planet: they're the ones pushing civilization forward. "Philosophically, I objected to the proposition that explorers into unknown realms represented the best and brightest of humanity; that progress could be achieved only by boldly venturing into unknown territories," Westfahl says. After all, a lot of smart and productive people (not to mention a lot of happy and stable people) don't spend their lives on the lam. "Clearly, history demonstrates no correlation between travel and virtue," he writes. "The history of our species powerfully suggests that progress will come from continued stable life on Earth, and that a vast new program of travel into space will lead to a new period of human stagnation," he concludes ominously.

In some ways, the desire for simpler living is part of what motivates space explorers. Astronauts are stuck with just a few people they have to get along with, or else they'll be miserable—a communal way of living that's more common to villages. They must make do with the nearby supplies or create their own, like

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people did before Walmart and Amazon. Communication with those beyond their immediate sphere is slow and difficult. They have a strict but straightforward and prescribed work schedule. Everything is a struggle; there are no conveniences. Unlike in a modern, digitally connected environment, their attention isn't split in many directions—they are focused on the present. Or at least that's how analog astronaut Ashley Kowalski felt during the SIRIUS 21 endeavor, an eight-month-long joint U.S.-Russia "lunar mission" that took place in a sealed space in Moscow.

Kowalski's talk at the Analog Astronaut Conference at Biosphere 2 was called "Only Eight Months." The goal of those eight months was to study the medical and psychological effects of isolation. She and her teammates regularly provided blood, feces and skin samples so researchers could learn about their stress levels, metabolic function and immunological changes. Researchers also had them take psychological tests, sussing out their perception of time, changes in cognitive abilities and shifts in interpersonal interactions. Inside they had to eat like astronauts would, guzzling tubes of Sicilian pizza gel and burger gel. Kowalski would squeeze them into rehydrated soup to make meals heartier. Via their greenhouse, they got about a bowl of salad between the six of them every three weeks.

Kowalski missed freedom and food and friends, of course. But the real struggle came with her return to the real world once the isolation was over: "reentry, not to the atmosphere but to the planet," she told the conference audience. She didn't remember how to go about having friends, hobbies or a job and had trouble dealing with requests coming from lots of sources instead of just mission control. In the Q&A period after the talk, Tara Sweeney, a geologist in the audience, thanked Kowalski for talking about that part of the experience. Sweeney had just returned from a long stay in Antarctica and also didn't quite know how to reintegrate into life in a more hospitable place. They had both missed "Earth," the real world. But it was hard to come back.

Still, the Analog Astronaut Conference crowd remained optimistic. "Where do we go from here?" conference founder and actual astronaut Sian Proctor asked at one point. On cue, the audience members pointed upward and said, "To the moon!"

Analog-astronaut work can't solve space travel's hardest problems—the intractable medical troubles, the in-red money questions, the touchy ethical quandaries. But while we all wait to see whether we'll ever truly migrate off this planet, and whether we should, these grounded astronauts will continue to escape Earth, for a time at least, without leaving it. ●

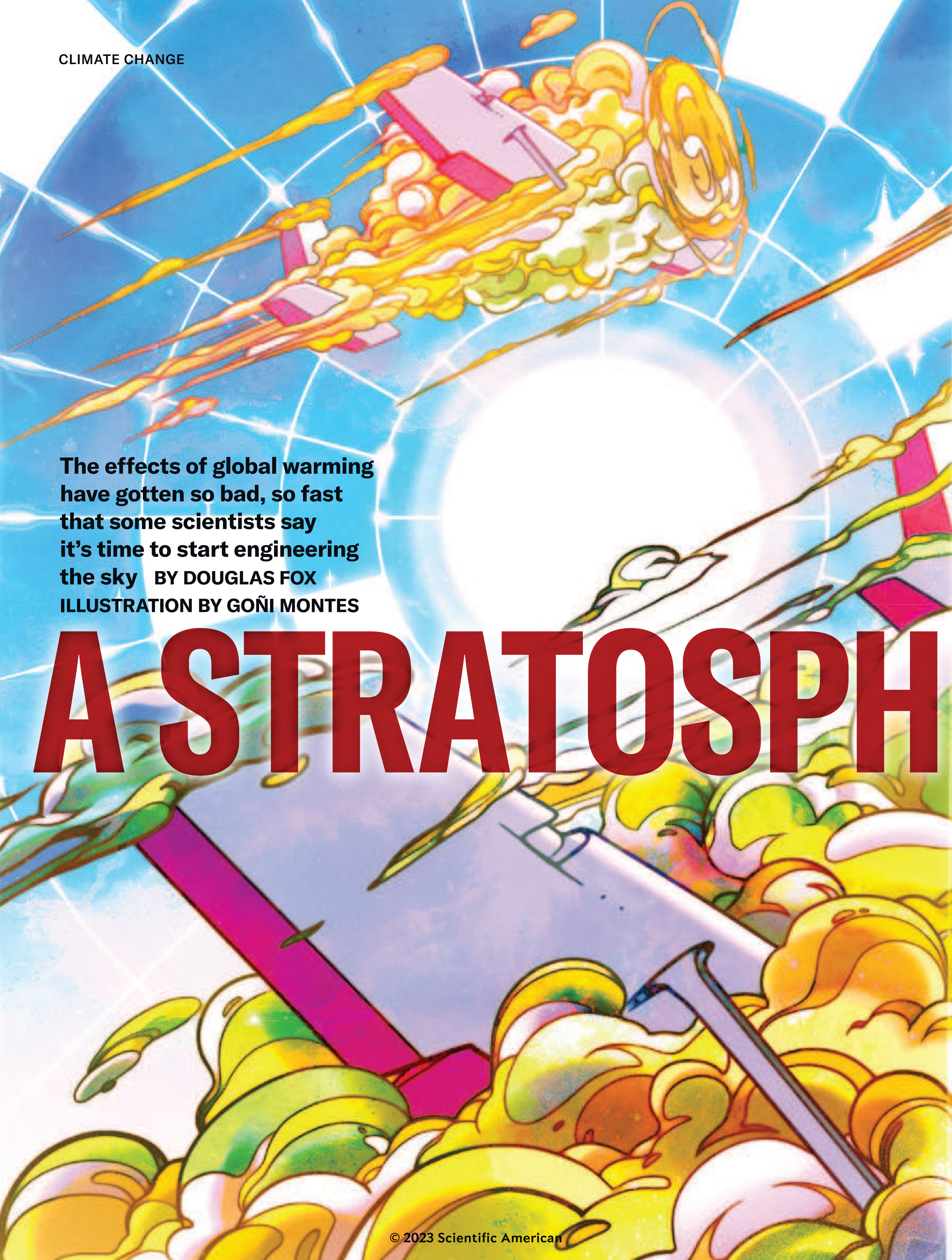
FROM OUR ARCHIVES

Lunar Land Grab. Adam Mann; July 2019. ScientificAmerican.com/magazine/sa

Celestial bodies, including our moon, are at risk of contamination by microscopic Earth life.

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A STRATOSPH

The effects of global warming have gotten so bad, so fast that some scientists say it's time to start engineering the sky BY DOUGLAS FOX

ILLUSTRATION BY GOÑI MONTES

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O **N THE CRISP** afternoon of February 12, 2023, two men parked a Winnebago by a field outside Reno, Nev. They lit a portable grill and barbecued a fist-sized mound of yellow powdered sulfur, creating a steady stream of colorless sulfur dioxide (SO_2) gas. Rotten-egg fumes permeated the air as they used a shop vac to pump the gas into a balloon about the diameter of a beach umbrella. Then they added enough helium to the balloon to take it aloft, attached a camera and GPS sensor, and released it into the sky. They tracked the balloon for the next several hours as it rose into the stratosphere and drifted far to the southwest, crossing over the Sierra Nevada Mountains before popping and releasing its gaseous contents. The contraption plummeted into a cow pasture near Stockton, Calif.

The balloon released only a few grams of SO_2, but the act was a brazen demonstration of something long considered taboo—injecting gases into the stratosphere to try to slow global warming. Once released, SO_2 reacts with water vapor to form droplets that become suspended in the air—a type of aerosol—and act as tiny mirrors, reflecting incoming sunlight back to space. Luke Iseman and Andrew Song, founders of solar geoengineering company Make Sunsets, had sold "cooling credits" to companies and individuals; a $10 purchase would fund the release of a gram of SO_2, which they said would offset the warming effects of a metric ton of atmospheric carbon dioxide for a year. They had planned a launch in Mexico but switched to the U.S. after the Mexican government forbade them.

Many people recoil at the notion of solar geoengineering, or solar radiation management (SRM), as it's often called. The idea that humans should try to fix the atmosphere they've messed up by messing with it some more seems fraught with peril—an act of Faustian arrogance certain to backfire. But as it becomes clear that humans are unlikely to reduce emissions quickly enough to keep global warming below 1.5 degrees Celsius, some scientists say SRM might be less scary than allowing warming to continue unabated. Proposals for cooling the planet are becoming more concrete even as the debate over them grows increasingly rancorous.

SRM replicates a natural phenomenon created by large volcanic eruptions. When Mount Pinatubo erupted in the Philippines in 1991, it blasted 20 million tons of SO_2 into the stratosphere, creating an "aerosol parasol" that cooled the planet by about 0.5 degree C over the next year or so before the droplets settled back to Earth. Studies suggest that if SRM were deployed at sufficient scale—maybe one quarter of a Pinatubo eruption every year, enough to block 1 or 2 percent of sunlight—it could slow warming and even cool the planet a bit. Its effects would be felt within months, and it would cost only a few billion dollars annually. In comparison, transitioning away from fossil fuels is expected to take decades, and the

Douglas Fox writes about biology, geology and climate science from California. He wrote the November 2022 article "The Coming Collapse," which revealed that Antarctica's Thwaites Ice Shelf could splinter apart in less than a decade.

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CO_2 emitted until then could make warming worse. Using machines to remove billions of tons of CO_2 from the skies, a process called direct-air capture, could slow warming but would be fighting itself—the machines might increase the world's energy consumption by up to 25 percent, potentially creating more greenhouse gas emissions. Because SRM could produce effects quickly, it has political appeal. It's "the only thing political leaders can do that would have a discernible influence on temperature within their term in office," says Ken Caldeira, a climate scientist emeritus at the Carnegie Institution for Science, who is also a senior scientist at Breakthrough Energy, an organization founded by Bill Gates.

Caldeira and others say SRM should be pursued with extreme caution—if at all. It could noticeably whiten our blue sky. It could weaken the stratospheric ozone layer that protects us and Earth's biosphere from ultraviolet radiation. It might change weather patterns and move the monsoons that water crops for billions of people. And it wouldn't do anything to remedy other CO_2-related problems such as ocean acidification, which is harming the ability of corals, shellfish and some plankton to form skeletons and shells.

Critics also say that the very idea of an escape hatch such as SRM could undermine support for reducing greenhouse gas emissions. Like a prescription drug, if SRM were used responsibly—temporarily and in small doses—it could be beneficial, easing what is likely to be a dangerously hot century or two and buying humanity some extra time to transition to renewable energy. But it also has potential for abuse. At higher doses it could increasingly distort the climate, altering weather patterns in ways that pit nation against nation, possibly leading to war.

For all these reasons, more than 400 scientists have signed an open letter urging governments to adopt a worldwide ban on SRM experiments. But other scientists are proceeding, if reluctantly. "All the scientists I know who are working on this—none of them want to be working on it," says Alan Robock, a climatologist at Rutgers University. Robock, who previously showed the world how a nuclear winter could shroud Earth, studies SRM out of a sense of obligation. "If somebody's tempted to do this in the future," he says, they "should know what the consequences would be."

Experts who support trials note that unabated warming is just as consequential. In a recent report, the World Meteorological Organization estimated a 66 percent chance that by 2027 the world's average annual temperature will briefly exceed 1.5 degrees C above preindustrial levels—a dangerous threshold beyond which extreme damage to the environment occurs. On February 27, 2023, a few days after Iseman and Song sent barbecued sulfur into the sky, 110 climate scientists, including climate change pioneer James Hansen, published a different open letter urging government support for SRM research. The following day the United Nations called for international regulations that could pave the way for experimentation. And in June the Biden administration released a report outlining what an SRM research program could look like.

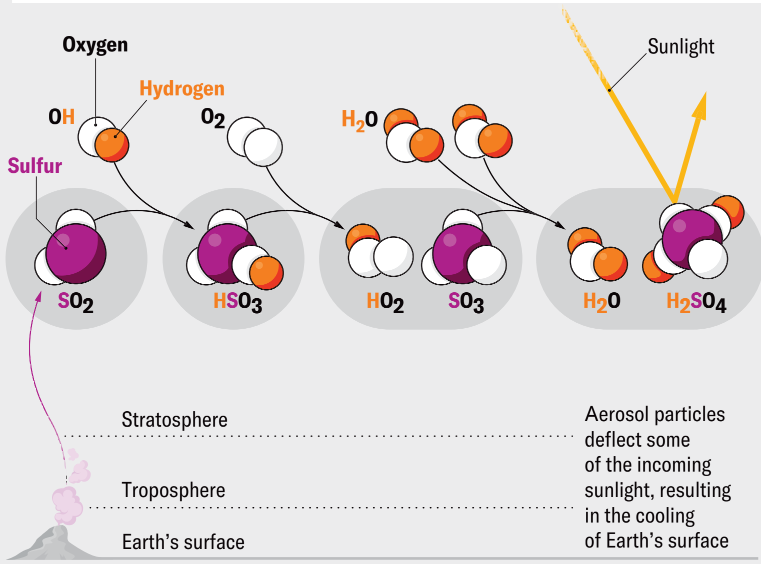
Even if SRM reduced average temperatures, it wouldn't reset the climate to its preindustrial state, says David Keith, head of climate systems engineering at the University of Chicago, who has studied the idea for over two decades. But it could lessen the hurt coming for us.

THE IDEA THAT HUMANS can change the planet's atmosphere for their own purposes has a long history. In 1962 the U.S. military started Project Stormfury, an attempt to weaken hurricanes by seeding their clouds with silver iodide particles. From 1967 to 1972 the U.S. Air Force dabbled in weather-control warfare over Vietnam and Laos; in a highly classified effort called Operation Popeye, several aircraft flew daily missions to spray lead and silver iodide powder into monsoon clouds. The goal was to increase rainfall, which would muddy up the Ho Chi Minh Trail, a network of coarse roads, interrupting Vietcong supply lines.

Almost as soon as scientists understood that rising CO_2 could warm the planet, some of them proposed making Earth more reflective to counter the effect. In 1965 scientists reported to President Lyndon B. Johnson that warming caused by rising CO_2 could be addressed by spreading reflective particles across the oceans. In 1974 Russian climatologist Mikhail Budyko

How Sulfur Dioxide Hides the Sun

Volcanoes, wildfires, and other sources produce sulfur dioxide (SO_2). As the gas rises to the stratosphere, chemical reactions create tiny sulfuric acid particles (H_2SO_4). The aerosols can linger in the atmosphere for up to three years, reflecting incoming energy from the sun and thereby lessening the warming of land and ocean surfaces.



Graphics by Lucy Reading-Ikkanda

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> "The most valuable experiment somebody could do now is one showing that there would be really horrible consequences."
> —Ken Caldeira *Carnegie Institution for Science*

suggested that injecting SO_2 into the stratosphere via aircraft or rockets could reflect sunlight. This technology, he wrote, "should be developed without delay." Perhaps surprisingly, these proposals did not include the idea of reducing emissions.

The idea of planet-scale engineering didn't gain much traction over the next two decades. When Lowell Wood, an engineer at Lawrence Livermore National Laboratory in California and an early proponent of the "Star Wars" missile defense system, stood up at the 1998 Aspen Global Change Institute conference to tout the cooling effects of stratospheric aerosols, the reception was chilly. "Ken [Caldeira] and I stood in the back room and almost shouted at him," Keith recalls. He "was completely overstating how well it would work." Their skepticism was based on simple logic: CO_2, by absorbing long-wave radiation rising from Earth, warms the planet uniformly from the equator to the poles year-round, day and night—whereas sunlight warms the planet mainly at lower latitudes, with stronger effects during the summer and the daytime. They thought dimming the sun would cool the planet unevenly, Caldeira says. "You get much more cooling at the equator," more cooling during summer, and less at the poles.

Caldeira returned to Livermore, where he also worked, and persuaded Govindasamy Bala, a climate scientist there, to test the idea with a sophisticated computer model. The model diminished incoming sunlight by 1.7 percent—enough to counteract the warming effects of CO_2 levels that were double what they had been in preindustrial years. "It worked a hell of a lot better than we expected," Caldeira says. The results, published in 2000, indicated that SRM would still cool the tropics a little more than the poles and make a bigger difference in summer than in winter, but overall the cooling would be far more uniform globally than Bala, Caldeira and Keith had thought.

A consortium of researchers that included Robock later replicated Bala's results across a dozen different climate models. But their 2013 findings revealed a red flag. As concentrations of stratospheric aerosols increased, the cooling grew less uniform, and the climate became more distorted. If stratospheric aerosols were used to offset the average warming caused by a quadrupling of CO_2 levels, the tropics would be 0.3 degree C cooler than in preindustrial times, but the polar regions would still be 0.8 degree C warmer. Permafrost and sea ice might not fully recover, meaning we would fail to reverse some of climate change's most damaging effects.

Bala discovered another worrisome detail: stratospheric aerosols might reduce rain and snowfall. Researchers knew that more warming increases the evaporation of water, leading to more precipitation, so it stood to reason that the reverse would also be true. But Bala found that dimming the sun could reduce rainfall *more* than it reduces temperature. That's because blocking sunlight, while leaving CO_2 high, slightly reduces the tendency of water vapor to form clouds. Simulations across the 12 models predicted that if SRM was used to fully counteract the warming of quadrupled CO_2, some parts of the tropics would receive 5 to 7 percent less annual rainfall compared with preindustrial times, potentially harming crops or tropical forests.

This and other observations led Keith and his colleagues to suggest a lower-dose approach to SRM in which stratospheric aerosol injections would be used temporarily to reduce the effects of climate change, buying nations time to cut greenhouse gas emissions and draw down (or "capture") CO_2 from the atmosphere.

Keith sketched out this scenario in a 2018 paper co-authored with climate scientists Douglas MacMartin of Cornell University and Katharine Ricke of the Scripps Institution of Oceanography. They envisioned a world in which greenhouse gas emissions are cut and carbon capture is deployed so that CO_2 peaks in 2070 at just over twice its preindustrial concentration before starting to slowly decline. This would cause roughly three degrees C of warming—a lot. To limit warming to 1.5 degrees C, stratospheric aerosol injections would be initiated around 2030 and slowly ramped up. Injections would peak in 2070 and be slowly reduced before being halted about two centuries later, when CO_2 levels had fallen sufficiently. Peter Irvine, a climate scientist at University College London, ran this scenario through 13 models. The results, published in 2019 in *Nature Climate Change,* showed that during the period of peak CO_2 concentrations, stratospheric aerosols would reduce warming and lessen precipitation extremes (including droughts and deluges) for 99.6 percent of the planet's ice-free land surface.

Other SRM methods might eventually be developed to even out the cooling. Marine-cloud brightening would involve spraying sea salt 1,000 meters into the air to seed the formation of cloud droplets, increasing the reflectivity of low-lying clouds over some parts of the ocean. In cirrus-cloud thinning, particles of silver iodide would be sprayed into clouds at altitudes of 4,500 to 9,000 meters, enlarging ice crystals in those clouds so they fell out of the sky. The remaining, thinner cirrus clouds would allow more long-wave radiation emanating from Earth to escape to space. Both methods would have more localized effects than injecting SO_2 would, so it might be possible to deploy them selectively to balance the effects of stratospher-

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ic aerosols, says Sarah Doherty, an atmospheric scientist at the University of Washington who studies marine-cloud brightening. "It may turn out that doing a little bit of each [method] would allow you to maximize benefits and minimize risks," she says.

STRATOSPHERIC AEROSOL INJECTION is the best-studied approach to solar geoengineering and the closest to deployment. But making it work would require overcoming major challenges. The atmosphere 20 kilometers up is neither Earth-like nor spacelike. At that altitude, roughly twice as high as commercial jets fly, the air pressure is just 5 percent of what we enjoy on the ground—low enough to spontaneously boil the fluids out of a person's mouth and lungs. Lift against an airplane's wing is minuscule. Only a handful of research planes worldwide can operate in air this thin. The best known is NASA's ER-2, a derivative of the U-2 spy plane with a tiny fuselage and gangling, oversized wings. It is piloted by a single human who must wear a full pressure suit, like an astronaut. It carries less than two metric tons of cargo.

ER-2s have flown more than 4,500 research missions in the past 50 years, sampling aerosols and gases in the stratosphere. They have refined our understanding of how ozone is destroyed. They have flown through volcanic eruption plumes. And they have helped to create the scientific foundation on which SRM is based. But these high-altitude albatrosses will never carry tons and tons of SO_2.

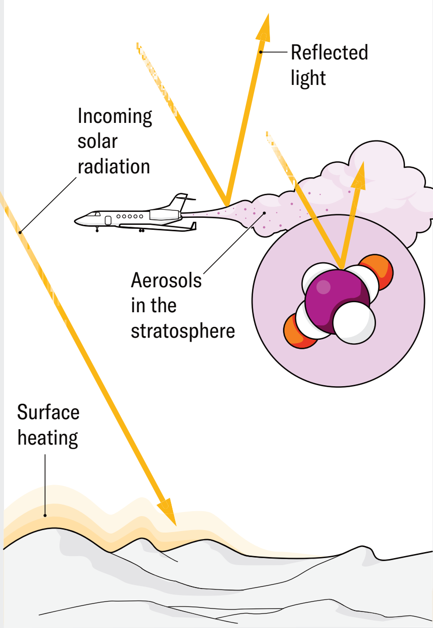
Planes capable of that job could be developed with largely existing technologies, says Wake Smith, a former aviation-industry executive and a climate researcher at the Yale School of the Environment. Since 2017 Smith has refined the concept of a six-engine plane based loosely on the B-47 Stratojet, a high-altitude U.S. Air Force craft designed in the 1940s to deliver nuclear bombs deep inside Soviet territory. Smith's Stratospheric Aerosol Injection Lofter would heft 15.7 tons of aerosol to a height of 20 kilometers every flight. Depending on how much SRM is desired, Smith envisions 90 to 900 planes flying missions every day by 2100. Building the first plane might take seven to 10 years; building a fleet could take 20 years.

Smith estimates that once the planes are built, the program might cost $18 billion annually per degree C of cooling. That's a small amount compared with the hundreds of billions of dollars a year it would take to remove billions of tons of CO_2 from the atmosphere. But SRM has a much higher chance than carbon remov-

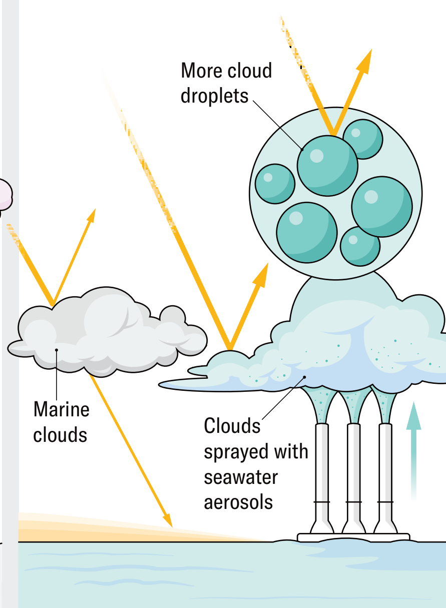
Engineering the Skies to Cool the Earth

Injecting aerosols into the stratosphere can limit incoming sunlight globally, reducing its heating effect on Earth. Other solar geoengineering techniques such as marine-cloud brightening and cirrus-cloud thinning can affect smaller regions.

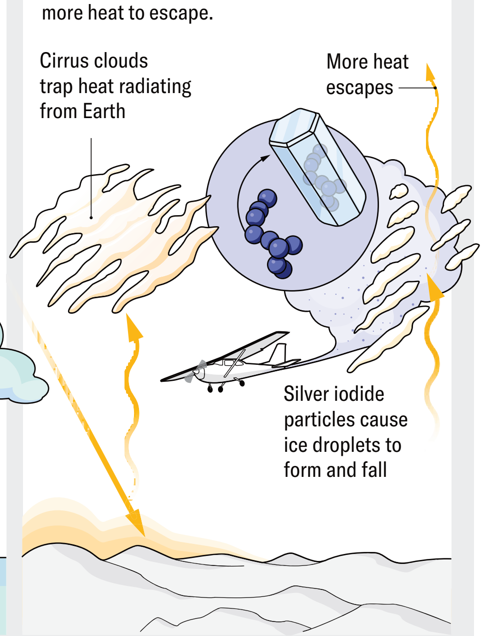
STRATOSPHERIC AEROSOL INJECTION
To lessen incoming sunlight worldwide by several percent, a fleet of 90 to 900 planes would fly into the stratosphere every day and release thousands of metric tons of sulfur dioxide, which would react to form aerosols that block incoming rays.



MARINE-CLOUD BRIGHTENING
Machines would spray salty seawater aerosols up into cumulus clouds, typically 300 meters to a kilometer high. That would increase the number of water droplets, making clouds denser, reflecting more incoming sunlight.



CIRRUS-CLOUD THINNING
High cirrus clouds trap more heat radiated from Earth than the heat they reflect from the sun. Spraying silver iodide particles into the clouds would enlarge ice crystals so they would fall as precipitation, thinning the clouds and allowing more heat to escape.



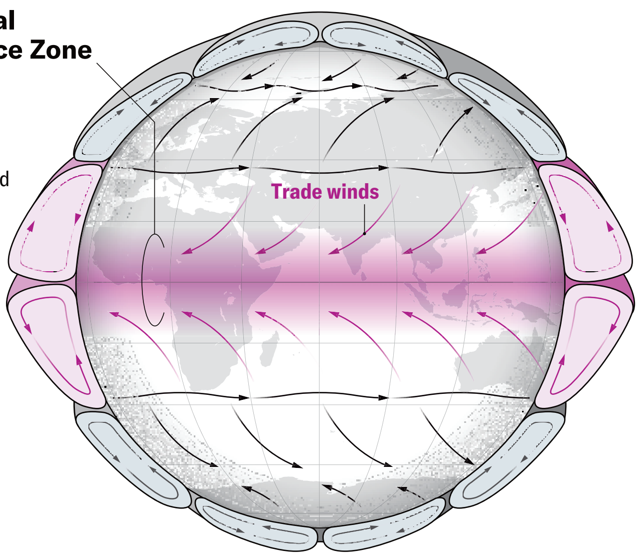
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al of causing nightmarish unintended consequences. Stratospheric injections by any country would affect the entire globe. Done wrong, they could disrupt weather patterns and the lives of billions of people.

A large fraction of humanity depends on a belt of thunderstorms and rain called the Intertropical Convergence Zone. The zone straddles the equator around the planet and shifts as far as 2,500 kilometers north or south with the seasons, pulled always toward the warmer hemisphere. Its movement spawns the monsoons that arrive each summer in India, Southeast Asia, Africa, and other regions, dropping more than 45,000 cubic kilometers of water annually, sustaining crops that feed 1.5 billion people in South Asia alone.

Intertropical Convergence Zone

The zone, formed by trade winds, affects rainfall and atmospheric circulation around the planet.



In 2008 Bala, the scientist at Livermore who first tested SRM in a model, moved to the Indian Institute of Science in Bangalore and began to study how human activities might affect that country's monsoons. His simulations showed that if aerosols were injected at the equator, they would spread over the Northern and Southern Hemispheres, with little impact on monsoon patterns. But some people have proposed a polar strategy in which aerosols would be injected at the high northern latitudes to slow rapid Arctic warming without overcooling the tropics. This well-intentioned proposal would have a "huge impact" on Indian monsoons, Bala says. His latest calculations, published in 2022, suggest that if injections sufficient to cool the planet by 1.5 degrees C were done at 30 degrees north, the monsoon band could shift southward by roughly 150 kilometers, reducing India's summer rainfall by up to 29 percent and threatening crops.

Bala's study demonstrates that stratospheric aerosol injection is never local; it inevitably has far-reaching effects. In 2021 Ricke modeled aerosol injections over the Indian Ocean meant to increase rainfall and reverse a long-standing drought in the semiarid Sahel region of North Africa. The intervention just shifted the droughts to a different set of nations, in East Africa. Another modeling study, in 2022, suggests that stratospheric aerosols could shift the burden of malaria from highland areas in East Africa to lowland areas in South Asia and sub-Saharan Africa. Some regions where the parasite currently thrives would become too cool for it; other places, currently too hot, would cool enough for it to take hold. These vast shifts in risk could harm "countries that are often outside the room when we're talking about geoengineering," says Christopher Trisos, an ecologist at the University of Cape Town in South Africa, who co-led the malaria study.

For all these reasons, Ricke says, SRM research is in "a very dangerous place." Most studies assume that it will be done in an internationally coordinated way, but she says modelers should also study scenarios in which injection is done haphazardly. Ricke, who also studies international relations, imagines a nightmare scenario in which individual countries, responding to heat waves, fires or floods, begin injecting aerosols unilaterally. Imagine that Russia initiates high-latitude injections to cool its Arctic regions. This action would push the monsoon belt southward, depriving India, Thailand and Vietnam of critical rain. It might also shift torrential rainfall farther south in Brazil, triggering floods. If these countries respond by beginning their own injections to lessen rainfall, a dangerous escalation could play out in the stratosphere. One country might even destroy another country's SRM aircraft, leading to a sudden rebound of warming and perhaps war. And the relatively low cost of SRM means many countries could afford it. "I think it's just inevitable that someone's going to try to do this," Ricke says.

PEOPLE WHO SUPPORT SRM point to studies showing that it could affordably reduce climate extremes. Critics point to studies showing the havoc it could cause. But the scientists who try to forecast effects will admit that most of these predictions contain huge uncertainties. The uncertainty begins with the models being used. Although SRM has shown consistent results in more than a dozen climate models, that's not because widely varied approaches are converging on the same answers. It's because "we have too many people running climate models that are similar," Keith says. If the assumptions underlying one model are wrong, then all the models might be wrong.

Models used to predict the effects of SRM contain dozens of variables representing physical parameters ranging from the chemical reactivity of aerosol droplets to their size. Tiny variations in the variables can have wide-ranging consequences. For example, a droplet that is one to two microns across (smaller than a red blood cell) should reflect sunlight most efficiently because its diameter is close to the wavelength of most incoming solar radiation. Larger droplets aren't just less effective—they could actually cause warming by absorbing long-wave radiation rising from Earth's surface that would otherwise escape to space. Anoth-

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er crucial variable is the rate at which droplets cause chemical reactions that destroy ozone. When researchers try to predict the effects of stratospheric injection, they plug in their best estimates for such variables. The problem is that most studies use similar estimates. "The big question," Keith says, "is, Are we wrong?"

To address this uncertainty, Keith recommends running large "ensembles"—hundreds of different versions of the same model in which different combinations of numbers are plugged in. Scientists have done only a few such studies of SRM effects. Keith hopes to oversee more ensemble work at the University of Chicago. The range of climate outcomes this research produces could then be plugged into models that predict how SRM could affect crop yields, forest fires, storms, or the spread of malaria and other diseases.

Still, no matter how many large ensembles scientists run, it's impossible to know how SRM will work until it's been tested in the real world—and tested at a much larger scale than two guys releasing a balloon outside Reno. In 2011 Keith and Caldeira published an analysis suggesting that a meaningful stratospheric-injection trial would take a decade. Several hundred thousand tons of SO_2 would have to be injected every year—enough, theoretically, to reverse 10 percent of the warming caused by a doubling of preindustrial CO_2 levels. The minimum viable experiment, in other words, "would be indistinguishable from a deployment," Caldeira says.

Smaller experiments could reduce uncertainties in the models. Scientists could get a better understanding of injection equipment, for example, by building it and using it to release anywhere from a few kilograms to a few metric tons of SO_2 into the stratosphere. That work could reveal whether ejected droplets remain the same size while aloft, details about chemical reactions, and what effects they have on ozone. In fact, scientists have been doing studies like this since the 1960s, releasing tracers such as zinc sulfide powder or sulfur hexafluoride gas into the stratosphere to study air currents.

But when the subject of inquiry is SRM, barriers to even small experiments become extreme. In early 2021 Keith and Frank Keutsch, an atmospheric chemist at Harvard, were planning the first SRM field trial. The Stratospheric Controlled Perturbation Experiment (SCoPEx) was designed to mimic a trail of aerosol released by a stratospheric aircraft. A self-propelled balloon would ascend 20 kilometers, release half a kilogram of sulfate into the wake of its propeller, then fly back through the aerosol trail to monitor how it evolved. The experiment would release only 0.3 percent of the amount emitted by a commercial transatlantic flight. The researchers planned for the first launch, slated for June 2021 in northern Sweden, to merely test the equipment without releasing any gas. It never happened.

In February 2021 the Sámi Council, a group representing Indigenous reindeer herders in the region, protested to the Swedish government that they had not been notified of the test occurring in their airspace. They, along with Greenpeace Sweden and several other environmental groups, persuaded the government to cancel it. The protests were never about the environmental impact of the test, MacMartin says. What happened, he says, is that "the entire conversation about 'Oh, my God, do we even want to go down this path?' got stapled onto that experiment."

MANY SRM OPPONENTS would like to ban experiments outright. Yet some scientists are continuing the research because they believe it's the responsible thing to do. "The people who should be advocating for experiments the most are the people who think that bad stuff would happen," Caldeira says. "The most valuable experiment that somebody could do now is one [showing] that there would be really horrible consequences." And if SRM is going to be studied and perhaps even rolled out, it's better to start sooner and more gradually, so the downsides can be understood. Ironically, SRM might have more public support if it were delayed until climate impacts become extreme, but at that point it would have to be done urgently and rapidly. "There's a real mismatch between what is politically and environmentally risky," Caldeira says.

Even small experiments will need the legitimacy of being funded and regulated by government, Kelly Wanser says. She is executive director of Silver Lining, a nonprofit organization that is encouraging the National Science Foundation and other government bodies to establish funding for SRM research and set up rules defining how and when experiments can be performed. Scientists would like that kind of governance, Ricke says. After all, it has long existed for other sensitive science areas, such as medical studies in humans, and has improved the quality of that research. The goal would be an international body, similar to the Intergovernmental Panel on Climate Change, that would set research priorities while considering the interests of rich and poor nations. Absent that structure, legitimate science is not progressing, Ricke says, and "rogue activities are starting to emerge."

Two months after the Reno balloon release, on April 10, Iseman and Song visited the Berkeley Marina in California to launch three more stratospheric balloons, funded by $2,840 of cooling credits purchased by customers. "A 747 emits this amount in a couple of minutes," Iseman said as he held high the first balloon in his right hand, with San Francisco Bay shimmering in the background and a camera crew filming. Then he let it go. A few days later the two men attended an Earth Day event in San Francisco, where they helped children launch their own small balloons, coated with chalk dust, which could aerosolize. "Our goal," Iseman said, "is to make 1,000 new geoengineers."

FROM OUR ARCHIVES

What Should Carbon Cost? Gilbert E. Metcalf; June 2020.
ScientificAmerican.com/magazine/sa

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FOOD

Wine's

A broad genetic study has revised the prevailing narrative about how wine grapes spread around the world

TEXT BY MARK FISCHETTI
GRAPHICS BY
FRANCESCO FRANCHI

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True Origins

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W**ITH JUST A** sniff and a sip, trained sommeliers can often tell what region a wine came from: Douro in Portugal, Barossa in Australia, Napa or Sonoma in California. Experts in a specific locale can name the hillside—even how far up the hill—where a wine's grapes were grown because of the terroir, the combination of soil, topography and microclimate that imparts a characteristic taste. The geographic and genetic journeys that brought those grapes to those places, however, have been poorly understood.

A massive new study gives us the clearest picture yet of the prehistory of wine, overturning several commonly accepted narratives about when and where humans cultivated grapevines to make the world's wines. A large international group of researchers collected and analyzed 2,503 unique vines from domesticated table and wine grapes and 1,022 wild grapevines. By extracting DNA from the vines and determining the patterns of genetic variations among them, they found some surprises.

For centuries grape growers in different communities passed down lore about where their grapes came from. Some governments, particularly in Europe, designated appellations—strictly circumscribed regions with rules on how and where a varietal such as burgundy, rioja or barolo was legally allowed to grow and be produced. But genetic studies to discover where vines originated thousands of years ago began in earnest only 10 or 15 years ago.

One theme that emerged from these studies was that wild grapes grew in central Asia and dispersed westward as early humans migrated in that direction. But the genetic data in the huge study correct this story, says Wei Chen, a senior research scientist at Yunnan Agricultural University in China and one of the study's leaders. Genetic data indicate that 400,000 and 300,000 years ago grapes grew naturally across the western and central Eurasian continent. Roughly 200,000 years ago a cold, dry, ice-age climate slowly killed off vines in the central Mediterranean Sea region, cleaving vine habitat into two isolated areas: one to the west of the sea (today Portugal, Spain and France) and one to the east (roughly Israel, Syria, Turkey and Georgia). Around 56,000 years ago the eastern region separated again into smaller isolated areas: the Caucasus (Georgia, Armenia and Azerbaijan) and western Asia (Israel, Jordon and Iraq).

Until recently, researchers also thought humans domesticated grapevines from wild progenitors as long as 8,000 years ago as an early agricultural revolution spread across what is now western Asia and Europe. Some experts thought vines were first cultivated in Iberia (primarily Portugal and Spain) around 3,000 years ago. Other investigators thought domestication first happened in the Caucasus. To make matters murkier (not a good trait in wine), there was disagreement on whether grapes were used first for food ("table grapes") or for fermentation.

The recent study settles this debate: humans in western Asia domesticated table grapes around 11,000 years ago. Other people, in the Caucasus, domesticated wine grapes around the same time—although they probably didn't master winemaking for another 2,000 or 3,000 years.

Early farmers, the revised story goes, migrated from western Asia toward Iberia and brought table vines with them. Along the way the farmers crossbred the table vines with local wild grapevines. The earliest crossbreeding probably happened in what is now Israel and Turkey, creating muscat grapes, which are high in sugar—good for eating *and* fermenting. Gradually the table grape was genetically transformed into different wine grapes in the Balkans, Italy, France and Spain.

But if people in the Caucasus already had wine grapes, why didn't they bring them to Europe? "We just don't know yet," Chen says. People migrating from there—notably Yamnaya nomads 4,000 to 5,000 years ago—might have brought vines, but the genetic analysis shows that Caucasus grapes have had very little influence on the makeup of European wine grapes.

Once farmers did begin cultivating wine grapes in Europe, they developed many of the varietals we enjoy today. Some grapes, such as cabernet sauvignon, have the same name everywhere they are grown. Other varietals farmed in different regions took on different names even though the grapes are genetically identical, such as zinfandel and primitivo. Sadly, it is almost impossible to trace a current varietal back to western Asia or the Caucasus, the two early domestication centers. Over the centuries grape growers crossbred table and wine grapes, as well as domesticated and wild grapes, and even back bred offspring with parents. "Once they had a superior vine, they usually destroyed the prior vines," Chen says, making it hard to construct a family tree. You may never know where your favorite wine came from—really came from. In that sense, the mystique lives on. ⬣

Mark Fischetti is a senior editor for sustainability at *Scientific American.*

Francesco Franchi is an infographic designer and deputy creative director of *la Repubblica*.

AndrewJohnson/Getty Images (*preceding pages*); Cosimo Calabrese/Getty Images (*opposite page*)

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Primitivo grapes are harvested in Puglia, one of Italy's famous wine regions.

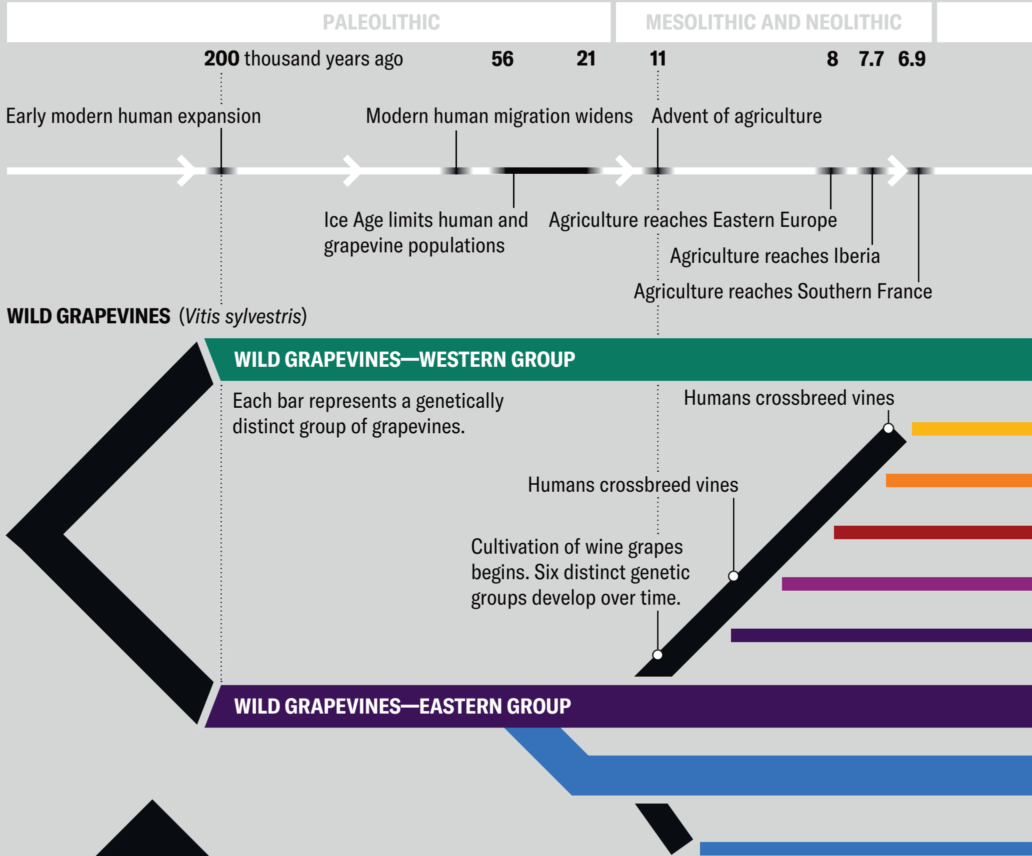
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How Grapevines Evolved

Wild grapevines from antiquity split about 200,000 years ago into two primary genetic lines, named western and eastern, and spread naturally across Eurasia. Humans who migrated there first domesticated wine and table grapes around 11,000 years ago as agriculture began to develop. Subsequent cultivation and crossbreeding led to six geographic lineages that largely make up the varietals we enjoy today.

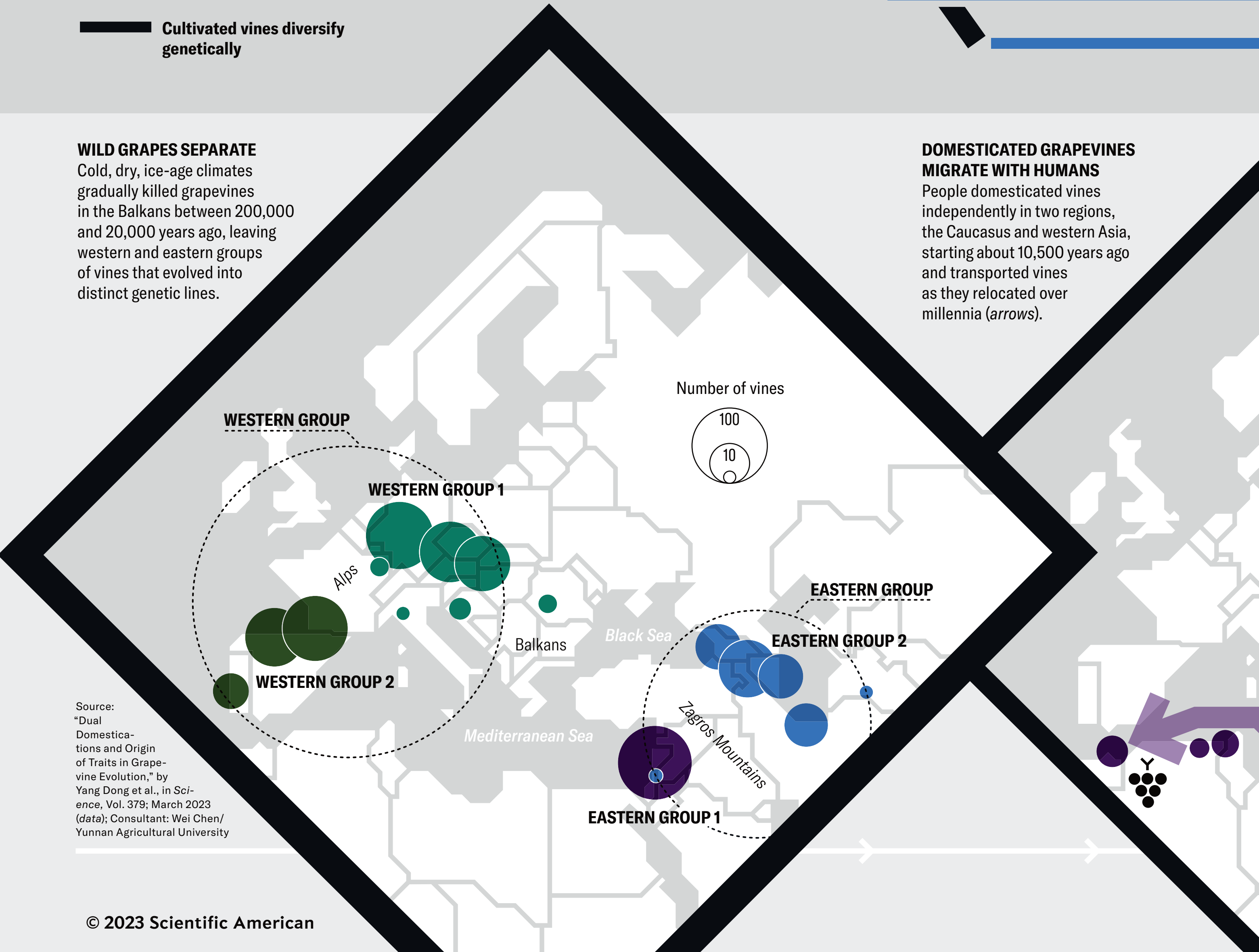
PHASE
The three primary waves of grapevine evolution are indicated with line thickness.

- **Wild vines separate into two geographic regions**
- **Domesticated wine vines migrate with humans**
- **Cultivated vines diversify genetically**



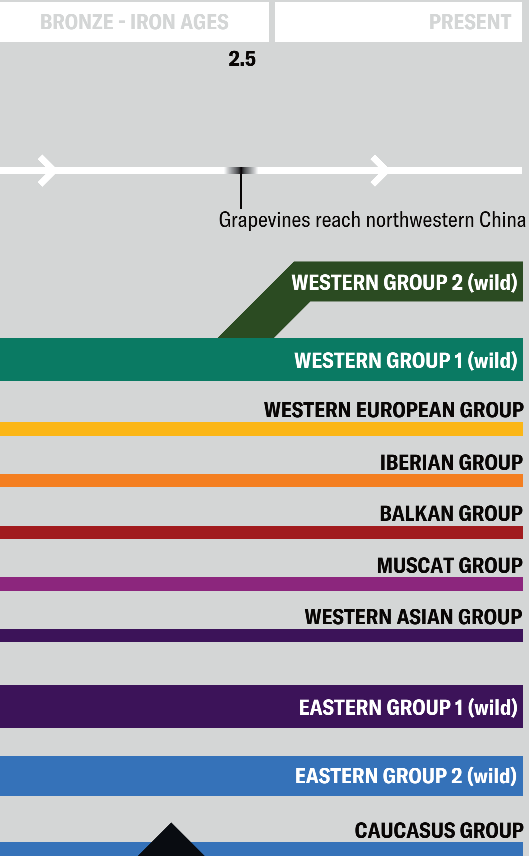
WILD GRAPES SEPARATE
Cold, dry, ice-age climates gradually killed grapevines in the Balkans between 200,000 and 20,000 years ago, leaving western and eastern groups of vines that evolved into distinct genetic lines.

DOMESTICATED GRAPEVINES MIGRATE WITH HUMANS
People domesticated vines independently in two regions, the Caucasus and western Asia, starting about 10,500 years ago and transported vines as they relocated over millennia (*arrows*).



Source: "Dual Domestications and Origin of Traits in Grapevine Evolution," by Yang Dong et al., in *Science*, Vol. 379; March 2023 (data); Consultant: Wei Chen/Yunnan Agricultural University

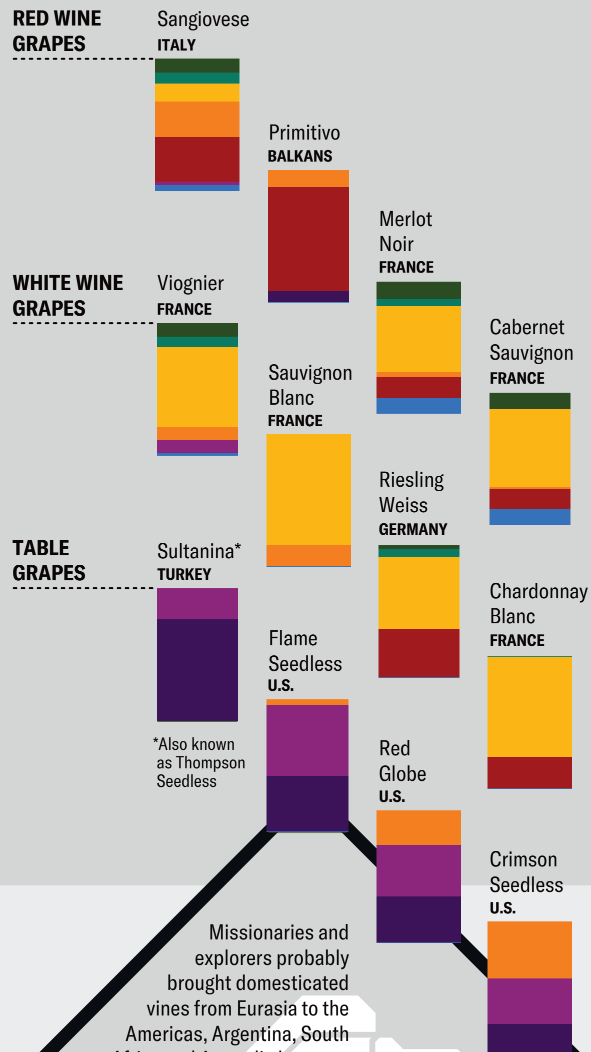
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ANCESTORS OF POPULAR MODERN GRAPES
The wines and grapes we love today have been bred from combinations of ancestral vines. Some, such as primitivo, are dominated by one set of vines (the Balkans, *dark red*). The western European vines (*yellow*) play a strong role in merlot, cabernet sauvignon and many white wines. The western, muscat and Iberian vines most greatly influence table grapes today.

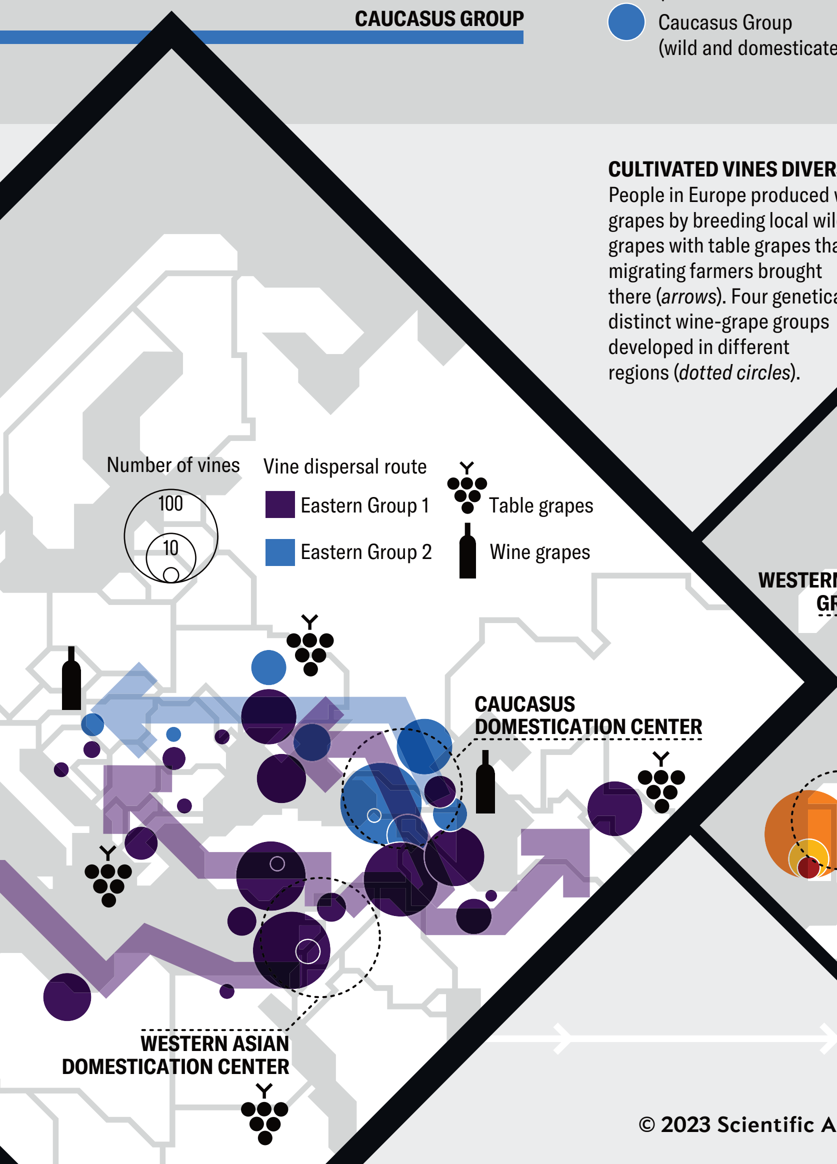
GRAPEVINE ANCESTRY

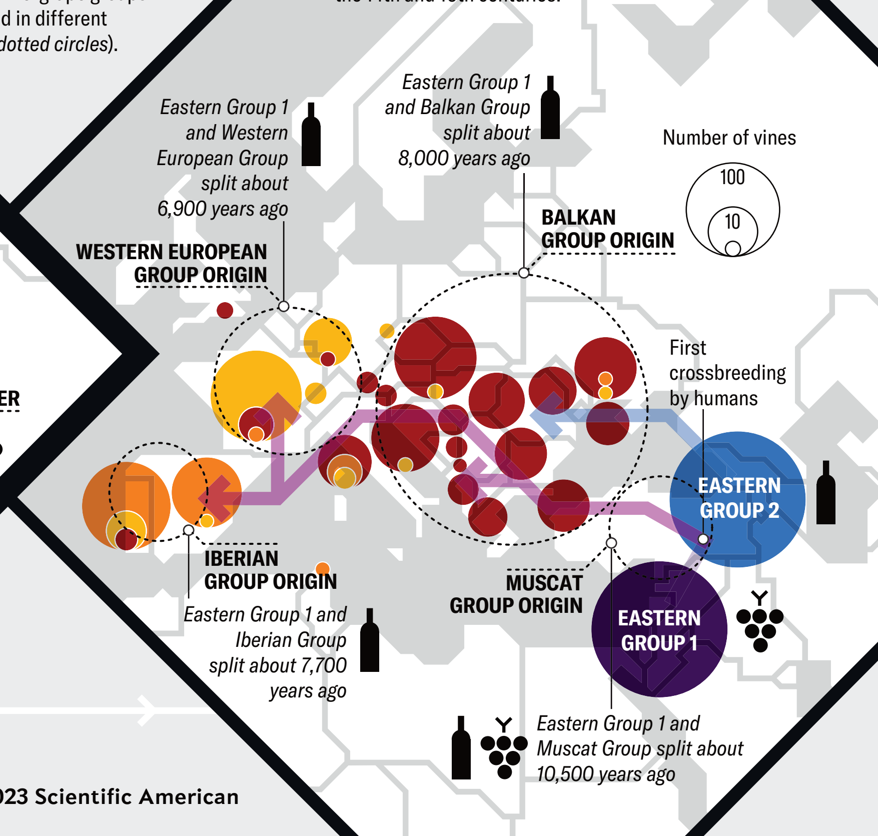
- Western Group 2 (wild)
- Western Group 1 (wild)
- Western European Group
- Iberian Group
- Balkan Group
- Muscat Group
- Western Asian Group (wild and domesticated)
- Caucasus Group (wild and domesticated)



CULTIVATED VINES DIVERSIFY
People in Europe produced wine grapes by breeding local wild grapes with table grapes that migrating farmers brought there (*arrows*). Four genetically distinct wine-grape groups developed in different regions (*dotted circles*).

Missionaries and explorers probably brought domesticated vines from Eurasia to the Americas, Argentina, South Africa and Australia between the 14th and 16th centuries.





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BEHAVIOR

Talking with



The Project Cetacean Translation Initiative (CETI) is using machine learning to try to understand the vocalizations of sperm whales.

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Animals

Artificial intelligence is poised to revolutionize our understanding of animal communication **BY LOIS PARSHLEY**

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UNDERNEATH THE THICK forest canopy on a remote island in the South Pacific, a New Caledonian Crow peers from its perch, dark eyes glittering. The bird carefully removes a branch, strips off unwanted leaves with its bill and fashions a hook from the wood. The crow is a perfectionist: if it makes an error, it will scrap the whole thing and start over. When it's satisfied, the bird pokes the finished utensil into a crevice in the tree and fishes out a wriggling grub.

The New Caledonian Crow is one of the only birds known to manufacture tools, a skill once thought to be unique to humans. Christian Rutz, a behavioral ecologist at the University of St Andrews in Scotland, has spent much of his career studying the crow's capabilities. The remarkable ingenuity Rutz observed changed his understanding of what birds can do. He started wondering if there might be other overlooked animal capacities. The crows live in complex social groups and may pass toolmaking techniques on to their offspring. Experiments have also shown that different crow groups around the island have distinct vocalizations. Rutz wanted to know whether these dialects could help explain cultural differences in toolmaking among the groups.

New technology powered by artificial intelligence is poised to provide exactly these kinds of insights. Whether animals communicate with one another in terms we might be able to understand is a question of enduring fascination. Although people in many Indigenous cultures have long believed that animals can intentionally communicate, Western scientists traditionally have shied away from research that blurs the lines between humans and other animals for fear of being accused of anthropomorphism. But with recent breakthroughs in AI, "people realize that we are on the brink of fairly major advances in regard to understanding animals' communicative behavior," Rutz says.

Beyond creating chatbots that woo people and producing art that wins fine-arts competitions, machine learning may soon make it possible to decipher things like crow calls, says Aza Raskin, one of the founders of the nonprofit Earth Species Project. Its team of artificial-intelligence scientists, biologists and conservation experts is collecting a wide range of data from a variety of species and building machine-learning models to analyze them. Other groups such as the Project Cetacean Translation Initiative (CETI) are focusing on trying to understand a particular species, in this case the sperm whale.

Decoding animal vocalizations could aid conservation and welfare efforts. It could also have a startling impact on us. Raskin compares the coming revolution to the invention of the telescope. "We looked out at the universe and discovered that Earth was not the center," he says. The power of AI to reshape our understanding of animals, he thinks, will have a similar effect. "These tools are going to change the way that we see ourselves in relation to everything."

Lois Parshley is an investigative journalist. Her climate reporting can be found on X (formerly known as Twitter) and Mastodon @loisparshley

WHEN SHANE GERO got off his research vessel in Dominica after a recent day of fieldwork, he was excited. The sperm whales that he studies have complex social groups, and on this day one familiar young male had returned to his family, providing Gero and his colleagues with an opportunity to record the group's vocalizations as they reunited.

For nearly 20 years Gero, a scientist in residence at Carleton University in Ottawa, kept detailed records of two clans of sperm whales in the turquoise waters of the Caribbean, capturing their clicking vocalizations and what the animals were doing when they made them. He found that the whales seemed to use specific patterns of sound, called codas, to identify one another. They learn these codas much the way toddlers learn words and names, by repeating sounds the adults around them make.

Having decoded a few of these codas manually, Gero and his colleagues began to wonder whether they could use AI to speed up the translation. As a proof of concept, the team fed some of Gero's recordings to a neural network, an algorithm that learns skills by analyzing data. It was able to correctly identify a small subset of individual whales from the codas 99 percent of the time. Next the team set an ambitious new goal: listen to large swathes of the ocean in the hopes of training a computer to learn to speak whale. Project CETI, for which Gero serves as lead biologist, plans to deploy an underwater microphone attached to a buoy to record the vocalizations of Dominica's resident whales around the clock.

Franco Banfi/Minden Pictures (*preceding pages*)

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As sensors have gotten cheaper and technologies such as hydrophones, biologgers and drones have improved, the amount of animal data has exploded. There's suddenly far too much for biologists to sift through efficiently by hand. AI thrives on vast quantities of information, though. Large language models such as ChatGPT must ingest massive amounts of text to learn how to respond to prompts: ChatGPT-3 was trained on around 45 terabytes of text data, a good chunk of the entire Library of Congress. Early models required humans to classify much of those data with labels. In other words, people had to teach the machines what was important. But the next generation of models learned how to "self-supervise," automatically learning what's essential and independently creating an algorithm of how to predict what words come next in a sequence.

In 2017 two research groups discovered a way to translate between human languages without the need for a Rosetta stone. The discovery hinged on turning the semantic relations between words into geometric ones. Machine-learning models are now able to translate between unknown human languages by aligning their shapes—using the frequency with which words such as "mother" and "daughter" appear near each other, for example, to accurately predict what comes next. "There's this hidden underlying structure that seems to unite us all," Raskin says. "The door has been opened to using machine learning to decode languages that we don't already know how to decode."

The field hit another milestone in 2020, when natural-language processing began to be able to "treat everything as a language," Raskin explains. Take, for example, DALL-E 2, one of the AI systems that can generate realistic images based on verbal descriptions. It maps the shapes that represent text to the shapes that represent images with remarkable accuracy—exactly the kind of "multimodal" analysis the translation of animal communication will probably require.

Many animals use different modes of communication simultaneously, just as humans use body language and gestures while talking. Any actions made immediately before, during, or after uttering sounds could provide important context for understanding what an animal is trying to convey. Traditionally, researchers have cataloged these behaviors in a list known as an ethogram. With the right training, machine-learning models could help parse these behaviors and perhaps discover novel patterns in the data. Scientists writing in the journal *Nature Communications* last year, for example, reported that a model found previously unrecognized differences in Zebra Finch songs that females pay attention to when choosing mates. Females prefer partners that sing like the birds the females grew up with.

YOU CAN ALREADY use one kind of AI-powered analysis with Merlin, a free app from the Cornell Lab of Ornithology that identifies bird species. To identify a bird by sound, Merlin takes a user's recording and converts it into a spectrogram—a visualization of the volume, pitch and length of the bird's call. The model is trained on Cornell's audio library, against which it compares the user's recording to predict the species identification. It then compares this guess to eBird, Cornell's global database of observations, to make sure it's a species that one would expect to find in the user's location. Merlin can identify calls from more than 1,000 bird species with remarkable accuracy.

But the world is loud, and singling out the tune of one bird or whale from the cacophony is difficult. The challenge of isolating and recognizing individual speakers, known as the cocktail party problem, has long plagued efforts to process animal vocalizations. In 2021 the Earth Species Project built a neural network that can separate overlapping animal sounds into individual tracks and filter background noise, such as car honks—and it released the open-source code for free. It works by creating a visual representation of the sound, which the neural network uses to determine which pixel is produced by which speaker. In addition, the Earth Species Project recently developed a so-called foundational model that can automatically detect and classify patterns in datasets.

Not only are these tools transforming research, but they also have practical value. If scientists can translate animal sounds, they may be able to help imperiled species. The Hawaiian Crow, known locally as the ʻAlalā, went extinct in the wild in the early 2000s. The last birds were brought into captivity to start a conservation breeding program. Expanding on his work with the New Caledonian Crow, Rutz is now collaborating with the Earth Species Project to study the Hawaiian Crow's vocabulary. "This species has been removed from its natural environment for a very long time," he says. He is developing an inventory of all the calls the captive birds currently use. He'll compare that to historical recordings of the last wild Hawaiian Crows to determine whether their repertoire has changed in captivity. He wants to know whether they may have lost important calls, such as those pertaining to predators or courtship, which could help explain why reintroducing the crow to the wild has proved so difficult.

Machine-learning models could someday help us figure out our pets, too. For a long time animal behaviorists didn't pay much attention to domestic pets, says Con Slobodchikoff, author of *Chasing Doctor Dolittle: Learning the Language of Animals.* When he began his career studying prairie dogs, he quickly gained an appreciation for their sophisticated calls, which can describe the size and shape of predators. That experience helped to inform his later work as a behavioral consultant for misbehaving dogs. He found that many of his clients completely misunderstood what their dog was trying to convey. When our pets try to communicate with us, they often use multimodal signals, such as a bark combined with a body posture. Yet "we are so fixated on sound being the only valid element of communication, that we miss many of the other cues," he says.

Now Slobodchikoff is developing an AI model aimed at translating a dog's facial expressions and barks for its owner. He has no doubt that as researchers expand their studies to domestic animals, machine-learning advances will reveal surprising capabilities in pets. "Animals have thoughts, hopes, maybe dreams of their own," he says.

Farmed animals could also benefit from such depth of understanding. Elodie F. Briefer, an associate professor in animal behavior at the University of Copenhagen, has shown that it's possible to assess animals' emotional states based on their vocalizations. She recently created an algorithm trained on thousands of pig sounds that uses machine learning to predict whether the animals were experiencing a positive or negative emotion. Briefer says a better grasp of how animals experience feelings could spur efforts to improve their welfare.

But as good as language models are at finding patterns, they aren't actually deciphering meaning—and they definitely aren't always right. Even AI experts often

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don't understand how algorithms arrive at their conclusions, making them harder to validate. Benjamin Hoffman, who helped to develop the Merlin app before joining the Earth Species Project, says that one of the biggest challenges scientists now face is figuring out how to learn from what these models discover.

"The choices made on the machine-learning side affect what kinds of scientific questions we can ask," Hoffman says. Merlin Sound ID, he explains, can help detect which birds are present, which is useful for ecological research. It can't, however, help answer questions about behavior, such as what types of calls an individual bird makes when it interacts with a potential mate. In trying to interpret different kinds of animal communication, Hoffman says researchers must also "understand what the computer is doing when it's learning how to do that."

DANIELA RUS, DIRECTOR of the Massachusetts Institute of Technology Computer Science and Artificial Intelligence Laboratory, leans back in an armchair in her office, surrounded by books and stacks of papers. She is eager to explore the new possibilities for studying animal communication that machine learning has opened up. Rus previously designed remote-controlled robots to collect data for whale-behavior research in collaboration with biologist Roger Payne, whose recordings of humpback whale songs in the 1970s helped to popularize the Save the Whales movement. Now Rus is bringing her programming experience to Project CETI. Sensors for underwater monitoring have rapidly advanced, providing the equipment necessary to capture animal sounds and behavior. And AI models capable of analyzing those data have improved dramatically. But until recently, the two disciplines hadn't been joined.

At Project CETI, Rus's first task was to isolate sperm whale clicks from the background noise of the ocean realm. Sperm whales' vocalizations were long compared to binary code in the way that they represent information. But they are more sophisticated than that. After she developed accurate acoustic measurements, Rus used machine learning to analyze how these clicks combine into codas, looking for patterns and sequences. "Once you have this basic ability," she says, "then we can start studying what are some of the foundational components of the language." The team will tackle that question directly, Rus says, "analyzing whether the [sperm whale] lexicon has the properties of language or not."

But grasping the structure of a language is not a prerequisite to speaking it—not anymore, anyway. It's now possible for AI to take three seconds of human speech and then hold forth at length with its same patterns and intonations in an exact mimicry. In the next year or two, Raskin predicts, "we'll be able to build this for animal communication." The Earth Species Project is already developing AI models that emulate a variety of species, with the aim of having "conversations" with animals. He says two-way communication will make it that much easier for researchers to infer the meaning of animal vocalizations.

In collaboration with outside biologists, the Earth Species Project plans to test playback experiments, playing an artificially generated call to Zebra Finches in a laboratory setting and then observing how the birds respond. Soon "we'll be able to pass the finch, crow or whale Turing test," Raskin asserts, referring to the point at which the animals won't be able to tell they are conversing with a machine rather than one of their own. "The plot twist is that we will be able to communicate before we understand."

The prospect of this achievement raises ethical concerns. Karen Bakker, a digital innovations researcher and author of *The Sounds of Life: How Digital Technology Is Bringing Us Closer to the Worlds of Animals and Plants,* explains that there may be unintended ramifications. Commercial industries could use AI for precision fishing by listening for schools of target species or their predators; poachers could deploy these techniques to locate endangered animals and impersonate their calls to lure them closer. For animals such as humpback whales, whose mysterious songs can spread across oceans with remarkable speed, the creation of a synthetic song could, Bakker says, "inject a viral meme into the world's population" with unknown social consequences.

So far the organizations at the leading edge of this animal-communication work are nonprofits like the Earth Species Project that are committed to open-source sharing of data and models and staffed by enthusiastic scientists driven by their passion for the animals they study. But the field might not stay that way—profit-driven players could misuse this technology. In a recent article in *Science,* Rutz and his co-authors noted that "best-practice guidelines and appropriate legislative frameworks" are urgently needed. "It's not enough to make the technology," Raskin warns. "Every time you invent a technology, you also invent a responsibility."

DESIGNING A "WHALE CHATBOT," as Project CETI aspires to do, isn't as simple as figuring out how to replicate sperm whales' clicks and whistles; it also demands that we imagine an animal's experience. Despite major physical differences, humans actually share many basic forms of communication with other animals. Consider the interactions between parents and offspring. The cries of mammalian infants, for example, can be incredibly similar, to the point that white-tailed deer will respond to whimpers whether they're made by marmots, humans or seals. Vocal expression in different species can develop similarly, too. Like human babies, harbor seal pups learn to change their pitch to target a parent's eardrums. And both baby songbirds and human toddlers engage in babbling—a "complex sequence of syllables learned from a tutor," explains Johnathan Fritz, a research scientist at the University of Maryland's Brain and Behavior Initiative.

Whether animal utterances are comparable to human language in terms of what they convey remains a matter of profound disagreement, however. "Some would assert that language is essentially defined in terms that make humans the only animal capable of language," Bakker says, with rules for grammar and syntax. Skeptics worry that treating animal communication as language, or attempting to translate it, may distort its meaning.

Raskin shrugs off these concerns. He doubts animals are saying "pass me the banana," but he suspects we will discover some basis for communication in common experiences. "It wouldn't surprise me if we discovered [expressions for] 'grief' or 'mother' or 'hungry' across species," he says. After all, the fossil record shows that creatures such as whales have been vocalizing for tens of millions of years. "For something to survive a long time, it has to encode something very deep and very true."

Ultimately real translation may require not just new tools but the ability to see past our own biases and expectations. Last year, as the crusts of snow retreated behind my house, a pair of Sandhill Cranes began to

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New Caledonian Crows, which are famous for their toolmaking abilities, have regionally distinctive vocalizations that could one day be deciphered using AI.

stalk the brambles. A courtship progressed, the male solicitous and preening. Soon every morning one bird flapped off alone to forage while the other stayed behind to tend their eggs. We fell into a routine, the birds and I: as the sun crested the hill, I kept one eye toward the windows, counting the days as I imagined cells dividing, new wings forming in the warm, amniotic dark.

Then one morning it ended. Somewhere behind the house the birds began to wail, twining their voices into a piercing cry until suddenly I saw them both running down the hill into the stutter start of flight. They circled once and then disappeared. I waited for days, but I never saw them again.

Wondering if they were mourning a failed nest or whether I was reading too much into their behavior, I reached out to George Happ and Christy Yuncker, retired scientists who for two decades shared their pond in Alaska with a pair of wild Sandhill Cranes they nicknamed Millie and Roy. They assured me that they, too, had seen the birds react to death. After one of Millie and Roy's colts died, Roy began picking up blades of grass and dropping them near his offspring's body. That evening, as the sun slipped toward the horizon, the family began to dance. The surviving colt joined its parents as they wheeled and jumped, throwing their long necks back to the sky.

Happ knows critics might disapprove of their explaining the birds' behaviors as grief, considering that "we cannot precisely specify the underlying physiological correlates." But based on the researchers' close observations of the crane couple over a decade, he writes, interpreting these striking reactions as devoid of emotion "flies in the face of the evidence."

Everyone can eventually relate to the pain of losing a loved one. It's a moment ripe for translation.

Perhaps the true value of any language is that it helps us relate to others and in so doing frees us from the confines of our own minds. Every spring, as the light swept back over Yuncker and Happ's home, they waited for Millie and Roy to return. In 2017 they waited in vain. Other cranes vied for the territory. The two scientists missed watching the colts hatch and grow. But last summer a new crane pair built a nest. Before long, their colts peeped through the tall grass, begging for food and learning to dance. Life began a new cycle. "We're always looking at nature," Yuncker says, "when really, we're part of it." ⬣

FROM OUR ARCHIVES

The Orca's Sorrow. Barbara J. King; March 2019.
ScientificAmerican.com/magazine/sa

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A SPECIAL REPORT FROM SCIENTIFIC AMERICAN AND NATURE

INNOVATIONS IN



ENVIRONMENTAL HEALTH EQUITY

PRODUCED WITH SUPPORT FROM TAKEDA PHARMACEUTICALS

Illustrations by Chiara Verchesi

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The Geography of Injustice

THE AIR WE breathe, the water we drink, the temperature outside—all are influenced by where we live, and each has a distinct effect on our health. Over the past few decades an abundance of research has shown that the environment can have dramatic impacts on health and that those who have the healthiest environments tend to have the most privilege. Conversely, those who bear the brunt of environmental health threats tend to have limited power to bring about real change.

Robert D. Bullard, known as the father of environmental justice, was one of the first people to systematically document the connection between race and exposure to pollution. His work showed clearly how U.S. policies such as redlining had burdened majority-Black communities with far more contaminated air and water than their white neighbors were exposed to. Because of those same historical policies, people of color on average live in neighborhoods with higher surface heat than do non-Hispanic white people. One result of these urban heat islands is that people who already have a higher risk of respiratory and heart disease end up living in environments that exacerbate those illnesses.

Around the world, people breathing the most toxic air are consistently the poorest and most disadvantaged. This pattern is apparent at every level, from the smallest towns to the largest countries. Wealthy nations have shown that reducing air pollution saves lives, and some poorer countries are proving that clean energy can fuel economic development.

Snakebite envenomation is one of the deadliest tropical diseases. Like so many other conditions, it is most dangerous to the people with the fewest resources because they are least able to protect themselves from being bitten or to access the best care. New treatments could save lives and limbs.

The climate crisis is changing the range and prevalence of many diseases. Valley fever has expanded into new locations, and those working outdoors in construction sites and dusty agricultural fields are the most at risk. The illness also disproportionately affects Latino, Asian and Indigenous American people, who are more likely to contract it than white people and who often experience more severe symptoms.

Solutions exist, and they require better understanding and a fresh approach. Innovative researchers are devising healthier buildings, designing clinical trials with community involvement, and monitoring the air and water to empower people to protect themselves. They are creating a movement toward a more livable and more just world.

—LAUREN GRAVITZ, CONTRIBUTING EDITOR

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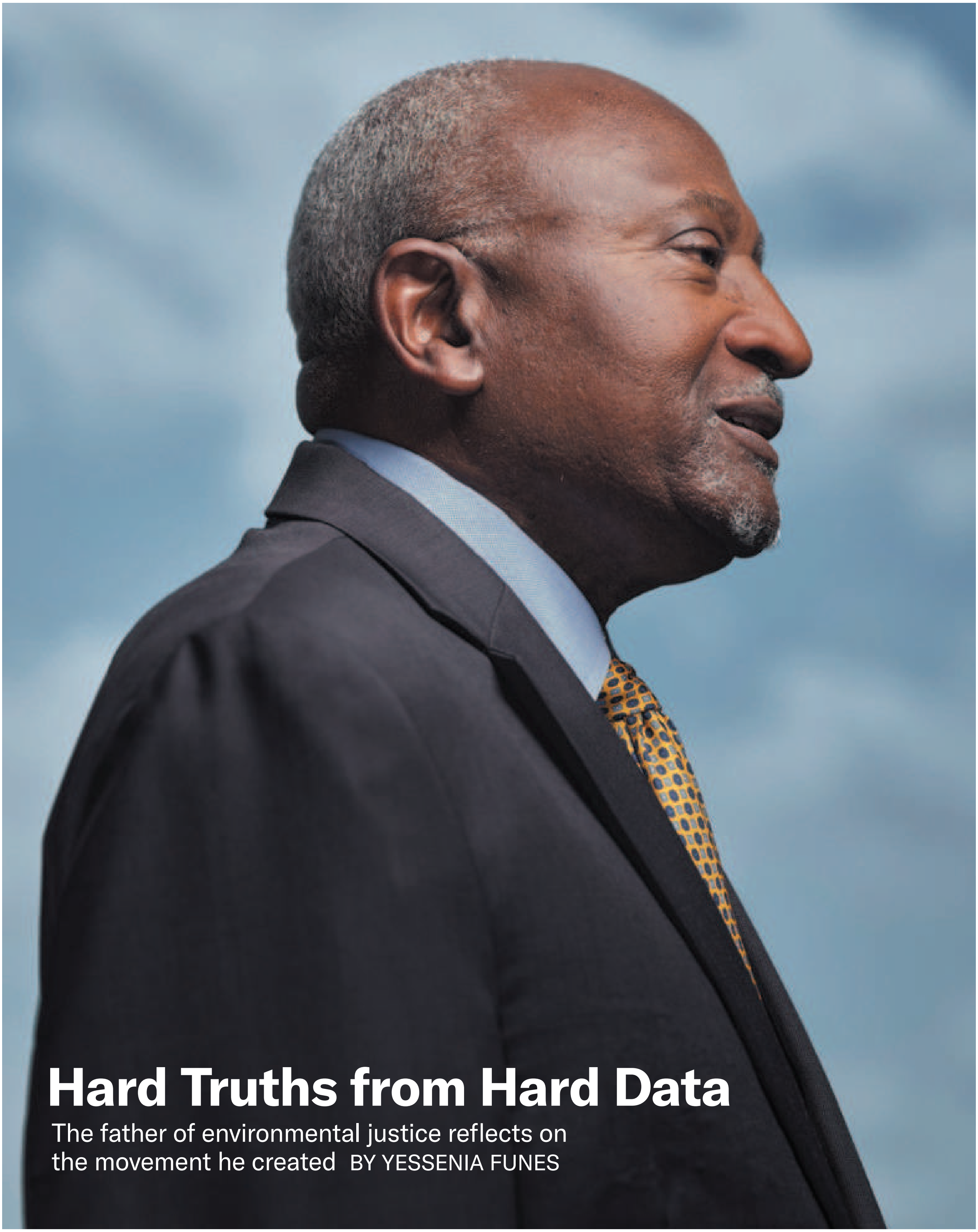
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Hard Truths from Hard Data

The father of environmental justice reflects on the movement he created BY YESSENIA FUNES

Photograph by Anthony Francis

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Black people face some of the highest cancer and asthma rates in the U.S., statistics that are inarguably linked to the environment in which someone lives, works and plays. But until Robert D. Bullard began collecting data in the 1970s, no one fully understood how a person's surroundings can affect their health. And no one, not even Bullard, knew how segregated the most polluted places really were.

Bullard was the first scientist to publish systematic research on the links between race and exposure to pollution, which he documented for a 1979 lawsuit. "This is before everyone had [geographic information system] mapping, before iPads, iPhones, laptops, Google," he says. "This is doing research way back with a hammer and a chisel."

In 2021 Texas Southern University in Houston established the Robert D. Bullard Center for Environmental and Climate Justice, where Bullard now serves as executive director. He has written 18 books on the topic, and his work helped to launch a movement. Environmental justice—the idea that everyone has the right to a clean and healthy environment, no matter their race or class—has been embraced by advocates around the world and is influencing international climate negotiations. SCIENTIFIC AMERICAN asked Bullard about his work and its impact in the U.S. and beyond.

An edited version of the interview follows.

Your early work signaled the start of a new field. How would you describe it?

I do what's called "kickass sociology." I've tried to pattern my work after a kickass Black sociologist: W.E.B. DuBois, who showed how someone can be a teacher, scholar, researcher, author, social critic and activist. He helped to found the NAACP [in 1909]—the oldest and largest civil rights organization in the U.S.—and he did some of the first empirical research in sociology.

Your first paper, in 1979, was the first to use hard data to quantify environmental racism. What prompted you to look into this?

The study was done in support of *Bean v. Southwestern Waste Management Corporation,* the first U.S. lawsuit to challenge environmental racism using civil rights law. The lawyer for that case was Linda McKeever Bullard, my wife at the time, and she needed numbers to back up the argument that locating solid waste landfills in a particular neighborhood was a form of discrimination. The community was middle class, suburban and an unlikely place for a garbage dump. It was also predominantly Black.

My job was to design the study, collect the data, and present maps that showed where all the landfills, incinerators and solid waste sites were located in Houston from the 1920s up to 1979. We found that five out of five of the city-owned landfills were in predominantly Black neighborhoods, as were three out of four of the privately owned landfills. Six out of eight of the city's incinerators were in Black neighborhoods. Black people made up only 25 percent of Houston's population at the time, yet 82 percent of the garbage in the city was dumped on them.

We lost in court because we couldn't prove it was intentional discrimination. It was easier to show scientifically that this pattern reflected a form of discrimination and not random data, but it's more difficult to prove it in court.

When you saw how widespread this pollution was in Black communities, what did you think?

I was surprised. I was amazed and shocked. But I was even more surprised and shocked and disappointed that the judge didn't see it. This was 40-something years ago. The judge was an old white man who was calling Black plaintiffs in the case "Negresses." That's a fancy, dressed-up way of calling you the N-word. The racial undertone was so thick. It was almost as if that case were brought too soon.

> Black people made up only 25 percent of Houston's population [in the 1970s], yet 82 percent of the garbage in the city was dumped on them.

What was the public response to your initial studies?

Communities on the ground, the ones who were being poisoned and ignored, started to come together. Grassroots and civil rights groups began to build coalitions and collaborate. By 1990 we were organizing the First National People of Color Environmental Leadership Summit. The industry attacked us. Some of us were sued. Some of us were intimidated and threatened. But we've kept fighting because we have justice on our side. A lot of people tried to debunk our work, but they never could. We had to fight with some of our environmental allies: conservation groups that were mostly white and affluent. They're with us now, but they were not always.

How have you built on those first studies?

I expanded my Houston study. I wanted to know whether the Houston example was an outlier. That's how the first book on environmental justice came about. I wrote *Dumping in Dixie* in 1989, but it took me a year to get that book printed. I had clear data showing that this discrimination was happening from Houston to Dallas, to the Louisiana Cancer Alley, to the Alabama Black Belt, to West Virginia. But the publishers said, "There's no such thing as environmental injustice. Everybody is treated the same. The environment is neutral."

All of what we've done since the Houston study has intentionally challenged the dominant paradigm. We argue that communities that have somehow been left out and left behind should be first in line when we talk about protection. Regulations should protect the most vulnerable populations, especially children of color.

Now environmental justice is not just in the U.S. It's global. It has been adopted into environmental reparations efforts. We talk about making our communities whole because of the damage the fossil-fuel industry has caused. We talk about repair-

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Hazardous Divisions

Few studies have assessed the racial composition of waste-adjacent neighborhoods. But building on Robert D. Bullard and his colleagues' 2007 work, Michael Mascarenhas and his collaborators extended the analysis to include 2010 census data. Their results are stark. More than 30 years after Bullard's Houston studies, the researchers found that a link between race and location of hazardous waste sites (host areas) in the U.S. persists. Also, income growth in host areas was much less than in nonhost areas even though both experienced the same increase in percentage of residents who lived below the poverty line.



*Data for U.S., excluding Alaska, Washington, D.C., Idaho, Montana and Wyoming.
**Host areas are U.S. census tracts in which at least 50% of their area lies within 3 kilometers (1.8 miles) of a commercial waste facility.
†Demographics labels reflect terminology used in the source.

Source: "Toxic Waste and Race in Twenty-First Century America: Neighborhood Poverty and Racial Composition in the Siting of Hazardous Waste Facilities," by Michael Mascarenhas, Ryken Grattet and Kathleen Mege, in *Environment and Society*, Vol. 12; 2021 (*data*)

ing our communities. In a global sense, reparations have translated into the Loss and Damage Fund, a pot of money established by higher-income countries at the 2022 United Nations Climate Change Conference. The fund aims to mitigate harm more developed countries have caused in less developed nations, which have contributed the least to climate change. They're feeling the pain and suffering first, worst and longest. It took 27 climate summits before the Loss and Damage Fund was adopted as a policy.

The road to where we are now has not been a bed of roses. We've always had detractors and people who have been well funded in fights against us.

What about global environmental racism and the importance of using a global lens?

We held our First National People of Color Environmental Leadership Summit in 1991, and representatives attended from the vast majority of U.S. states, as well as several foreign countries and tribal nations. Our principles of environmental justice—which include the safety of workers, the rights of Indigenous peoples and the honoring of nature—have been translated into half a dozen languages. And globally, in countries that have suffered because of colonialism, imperialism and racism, communities are now applying that same environmental justice lens to their organizing. Our principles of environmental justice resonated with the Global South. Those countries that have contributed the least to climate change are feeling that pain and suffering right now, as they have been for decades.

The environmental and climate justice framework that we use for the research in the U.S. has expanded to universities across the world: South Africa, Australia, Scotland. In some cases, they use not a racial lens but an equity lens that looks at gender, income, former colonization status, and market forces that have stripped people of the power to decide for themselves whether they want a new project in their communities.

Graphics by Miriam Quick and Jen Christiansen

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This research is supported by the framework that we set in place, one that uses a community-university partnership. The people who are most negatively impacted also carry knowledge and solutions. These decisions affect their homes, their families and their lives, so it's important that they remain involved. Community science is probably the fastest-growing part of the global climate and environmental justice movement.

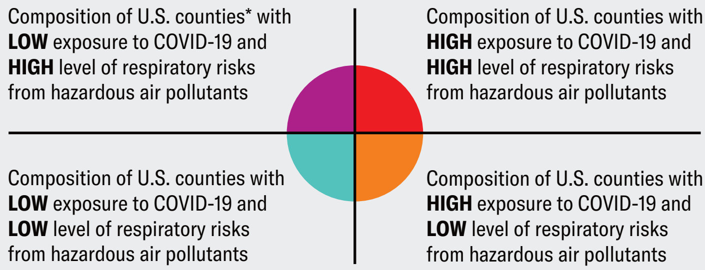
How did race come to be such a defining factor in the U.S. for who gets clean air or water and who does not?

Racism is deeply ingrained in America's DNA. Race has always played a significant part in who's free, who gets educated and who is a citizen. There was slavery, then emancipation and Jim Crow segregation, where "separate but equal" was codified. If a Black person, for example, paid the same taxes as a white person, those taxes were not spent in a way that gave them equal protection and treatment.

The Civil Rights Act was wasn't passed until 1964. Racial redlining drew a line around Black and brown neighborhoods, labeling them as dangerous and undesirable for loans. That prevented our neighborhoods from benefiting from infrastructure such as sewer and water systems.

Unbalanced Exposure

A range of variables, including air pollution and COVID-19 infections, can affect respiratory health. Those risks are not evenly divided. An analysis by Jayajit Chakraborty, published in 2021, shows that people of color—as well as people who are poor and uninsured—are overrepresented in areas that experienced both high levels of hazardous air pollution and high rates of COVID early in the pandemic.





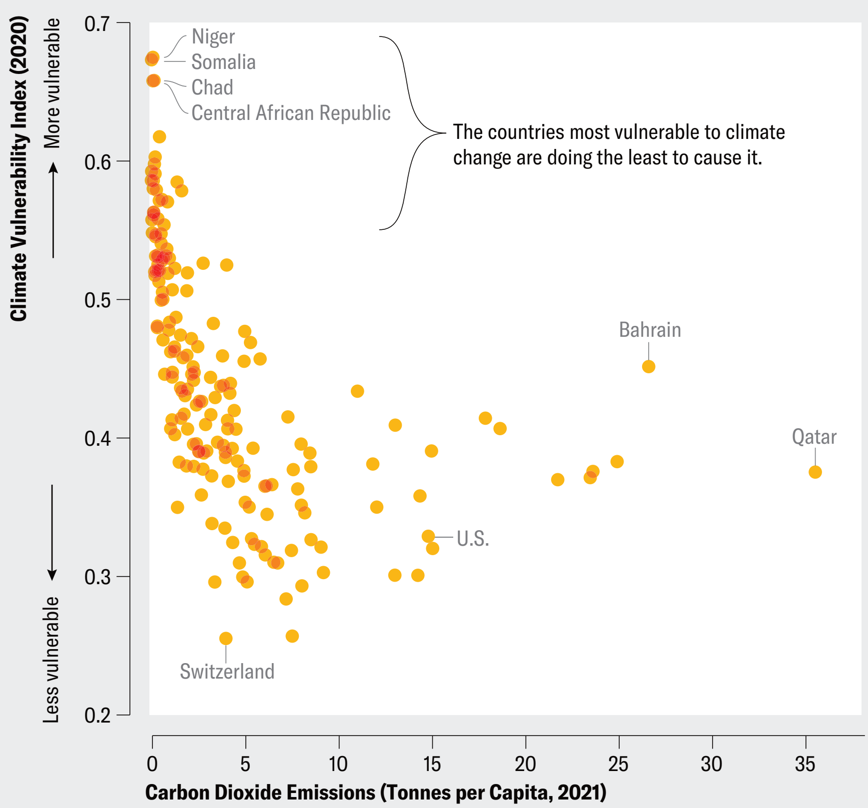
*Study included 3,107 U.S. counties. Nearly 50% (1,515 counties) did not yield statistically significant results and are not included in these charts.
†Demographics labels reflect terminology used in the source.

Source: "Convergence of COVID-19 and Chronic Air Pollution Risks: Racial/Ethnic and Socioeconomic Inequities in the U.S.," by Jayajit Chakraborty, in *Environmental Research*, Vol. 193; 2021 (data)

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Climate Vulnerability

Countries that emit more carbon dioxide per capita tend to be less vulnerable to the effects of those emissions than other regions are. This conclusion is based on data from the Notre Dame Global Adaptation Initiative's country index, which quantifies a country's vulnerability to climate hazards based on a number of variables—exposure, sensitivity and ability to adapt across six areas: food, water, health, ecosystem service, human habitat and infrastructure. Higher index values reflect higher levels of vulnerability. When a country's index value is plotted against its per capita carbon emissions, a trend becomes visible and illustrates the vulnerability of less industrialized nations.



Sources: Global Carbon Institute via Our World in Data (*carbon dioxide emissions data*); Notre Dame Global Adaptation Initiative (*climate vulnerability index data*)

We're now seeing the legacies of that racism. Neighborhoods that were redlined 100 years ago are hotter today because of urban heat islands [see "Islands of Illness," on page S26]. They have no tree canopy or parks or green space. They're more prone to flooding because they lack flood protection. They are more prone to industrial pollution. And we've learned that the same neighborhoods were more prone to COVID hospitalizations and deaths.

These are all examples of how past racism keeps getting transferred forward: it increases vulnerability.

You've been doing this for almost 50 years now. What keeps you going?

I've seen environmental justice move from a footnote to a headline, which means we are making inroads and progress in research and in policy. Even though we've made strides, we have a long way to go. Just having the data has never been enough. We must take these findings and convert them to policy. You have to marry facts with action, and there's not been enough action—even after all the reams and reams of studies.

What comes next for you?

We have a couple of projects. One is our participation in the U.S. government's Justice40 Initiative, which is funded by the Bezos Earth Fund. It looks at how our center can work with communities and use our HBCU [historically Black college or university] consortium to help communities that have been underserved and invisible when it comes to issues around climate, economic development, housing, transportation and clean energy.

Another is a Bloomberg project we're participating in that looks beyond petrochemicals. How do we explore transitioning to a clean energy economy and, at the same time, make sure that transition is equitable, fair and just?

We are helping community-based organizations in Texas resist the 80-plus new oil and gas facilities proposed for Houston, Beaumont-Port Arthur and Corpus Christi—areas already impacted by petrochemical plants. This is complemented by a study we're doing that examines the environmental justice implications of rapid permitting and build-out of terminals for liquefied natural gas in the Gulf Coast. Ironically, many of the new facilities are being proposed in communities where most residents have low incomes or are people of color and where they are already burdened with petrochemical plants.

We're also looking at the Inflation Reduction Act and the extent to which our center can collaborate with other organizations to ensure a holistic approach when we talk about greenhouse gas reduction. When we talk about cutting emissions, we're also talking about creating green jobs and about supporting small-business entrepreneurs so they can be creative and innovative. It's about getting more of our young people of color interested in science, technology and engineering so we can build out a pipeline for the future.

The environmental and climate justice movement today is intergenerational, and that's exciting. I've been doing this for 40-plus years. I'm a Boomer and proud of it—still fighting and still standing. But the fact is, Millennials and Zoomers and Gen Xers combined outnumber my generation. We need to develop a strong intergenerational partnership so these younger people don't have to hit brick walls.

We will get to the point where we will address all these challenges we have faced. Many are artificial barriers that we can break down to move more quickly toward solutions. We can take this quest for justice and pass the baton. That's how we will cross the finish line. ⬢

Yessenia Funes is a journalist who has covered environmental and climate justice for nearly a decade. She serves as editor at large for *Atmos*, a magazine dedicated to climate and culture, and publishes a weekly independent creative climate newsletter called *Possibilities*.

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Breathtaking Bias

Air pollution is concentrated in the most vulnerable communities, and reducing it could improve health equity worldwide BY JYOTI MADHUSOODANAN

Dolores Perales was 10 years old the first time she couldn't take a breath and thought she was going to die. Parts of the memory remain vague: she knows it was early April, the start of softball season, and she was playing outside. What she remembers clearly is the tightness in her chest and the rising panic. After it happened repeatedly, her mother took her to a doctor, who diagnosed her with asthma. "Ever since then I just had my inhaler," she says. "One of my younger brothers had asthma; my cousin across the street had asthma. So many of the kids in my classroom had asthma," Perales says. "As a kid, you kind of start thinking this is something normal."

Equally normal, as far as Perales was concerned, was a Detroit skyline hazed by the fume-spewing Marathon petroleum refinery. And the Ambassador Bridge—the busiest vehicle crossing between the U.S. and Canada, often packed with idling, diesel-fueled trucks—was typical, too. Both were within a few miles of her home.

It was not until Perales began traveling with her middle school softball, volleyball and basketball teams that she realized the chemical-laced air she knew so well was not the norm for everyone. Just a 30-minute drive from her own neighborhood, Perales encountered quiet, tree-lined streets. But even more striking to her than the greenery was the suburban air. "It smelled different," she says. "When I was out there, it didn't smell bad."

Nearly a decade after that first asthma attack, Perales began attending college at Michigan State University, where the air was so pristine that she rarely needed her inhaler. A few years later, during graduate courses in environmental justice, Perales learned that the emissions in the air that made her so sick were a direct result of discrimination—the refinery and the bridge had been placed where they were because, years before, her community had been deemed less important than the well-to-do suburbs and had neither the means nor the political influence to fight back. Air pollution had become concentrated in her neighborhood as one of the side effects of a discriminatory housing practice known as redlining.

Even when a nation's overall air quality is safe, pockets of polluted air may persist—often in areas where marginalized communities live and work. In the U.S., redlining and practices such as building freeways through poorer neighborhoods have exposed some people to much higher levels of pollution than those in adjacent neighborhoods.

"The major sources of emissions of harmful pollutants are often placed, in unfair ways, in communities that are disadvantaged as a result of discriminatory or racist practices or policies," says environmental health researcher Rima Habre of the University of Southern California.

In countries around the world the burden of poor air quality—and its accompanying health threats—typically falls on lower-income communities, including immigrants, migrant workers and people from other marginalized groups. Any improvements in air quality tend to start in richer neighborhoods. On a global scale, people in high-income countries breathe cleaner air than those in low- and middle-income countries.

Improving air quality is one of the biggest opportunities the world has to save lives and reduce health inequities. In one 2011 estimate, the Environmental Protection Agency predicted that the Clean Air Act would prevent about 230,000 early deaths in 2020 alone. Another U.S.-based study, this one from 2022, estimated that reducing pollution from energy production could save an additional 50,000 lives every year. Such policies could go even further if health equity is factored into policymaking, experts say.

Over the past few decades efforts to learn more about air-pollution risks have led to a greater understanding of the inequity of exposure and how it contributes to health disparities. As Susan Anenberg, an environmental health expert at the George Washington University, says, "We can now get down to a pretty granular scale when thinking about who receives the health benefits of improved air quality and who is still having to deal with the repercussions of poor air quality."

DOWNWIND THREATS

In the 19th century smoke from inefficient coal fires became one of the first signs of increasing wealth as cities and industries expanded. Coal and petroleum products remain among the primary sources of air pollution around the world. In other words, economic growth still taints the air.

In some places, smoke was considered an aesthetic problem but not necessarily a medical one. Most people were "only concerned with that which was visible," says historian Awadhendra Sharan of the Center for the Study of Developing Societies in Delhi, India. "There's this long-standing view that there is something aesthetically wrong with a polluted atmosphere."

In the U.S., efforts to protect more privileged communities from ugly emissions pushed the dirty air into neighborhoods like Perales's in southwestern Detroit, which were home to immigrant, Black and Hispanic families. The infrastructure needed to support the city, such as the Marathon petroleum plant and the Ambassador Bridge, had to be placed somewhere, "and that somewhere was here," Perales says. "This was an area that was considered undesirable."

It's only in the past 75 years—after events such as the deadly 1948 smog in Donora, Pa., and London's Great Smog, which killed 4,000 people in 1952—that more researchers, physicians and activists began to recognize the health risks of dirty air.

Air pollution endangers almost every aspect of human health. The worst threat comes from tiny particles, known as $PM_{2.5}$, that are 2.5 microns or less in diameter. Once inhaled, they can cause or exacerbate respiratory diseases such as asthma, chronic obstructive pulmonary dis-

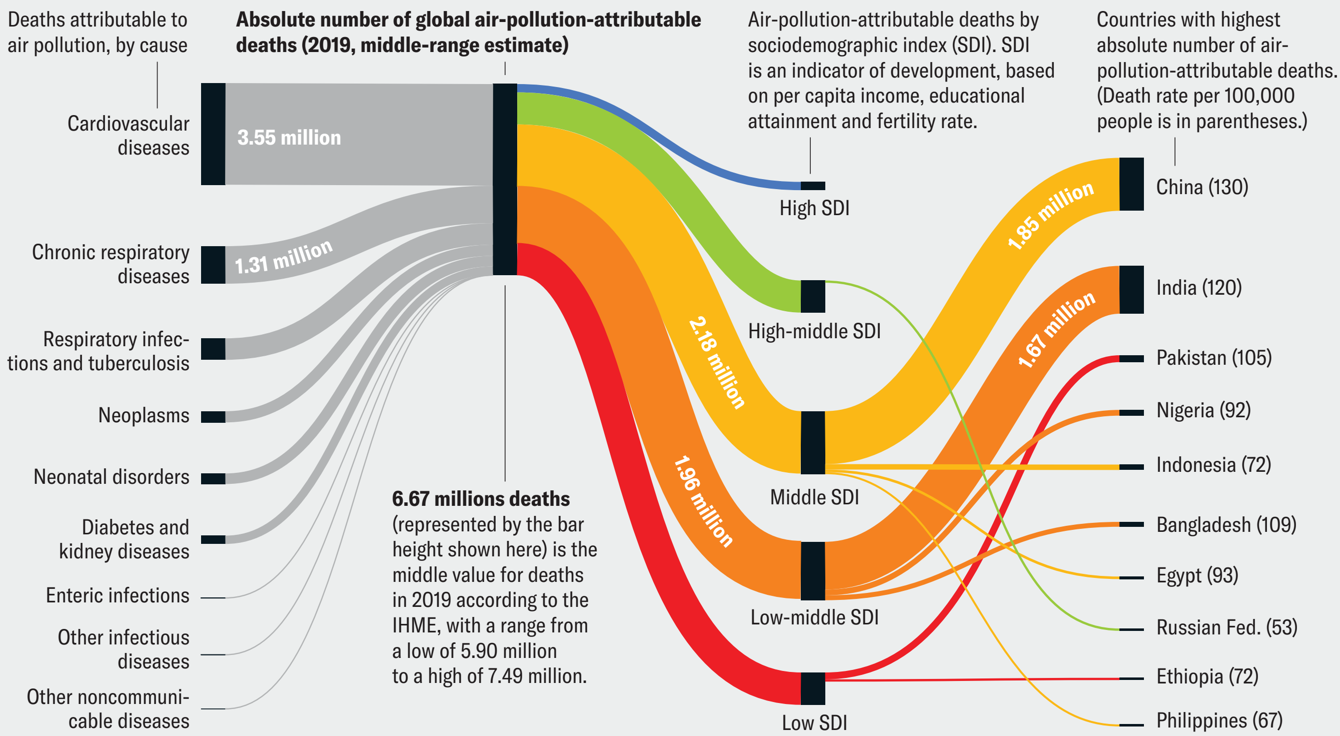
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Death by Air Pollution

Exposure to indoor and outdoor air pollution increases the risk of developing life-threatening diseases. Estimates of the global death toll from air pollution are substantial but still in flux—researchers are constantly reassessing the connection between pollution and diseases, a connection that is growing stronger all the time. The Global Burden of Disease study from the Institute for Health Metrics and Evaluation (IHME) suggests that about 6.7 million global deaths in 2019 were a result of air pollution. A partial breakdown of the study's results is shown here. As scientists learn more about the contribution of air pollution to disease, the numbers will continue to shift.



ease and lung cancer. These minute particles slip through layers of lung tissue to enter blood vessels and affect major organs such as the heart, kidneys and liver. They cause inflammation that touches every part of the body, including the brain, and have been linked to heart disease, neurodegenerative illnesses and even dementia. "It seems as though pretty much every organ system can be affected by pollution," says environmental health researcher Michael Brauer of the University of British Columbia and the University of Washington.

People who feel the health impacts most keenly are those who live or work near sources of pollution, such as oil refineries, coal-burning power plants or freeways with smoke-spewing trucks. Numbers can swing wildly from day to day, but $PM_{2.5}$ levels can get six to eight times higher in pollution hotspots than in neighboring areas. "Many of those very local hotspots of air pollution are inequitably distributed, in the U.S. especially, on the basis of race and socioeconomic status," Brauer says.

Globally, the degree of risk from deadly air correlates with a person's income and social class. The pattern can be seen at every scale, whether looking at the difference in wealth across nations, neighborhoods within a city or neighbors in a small town. When Brauer was conducting studies of air quality in villages across Mexico and India, he could tell which families were most likely to breathe more dangerous air based solely on signs of poverty.

"We see this pattern across the world, and you can even see it within a single village," Brauer says. He has noticed that poorer families tend to live crowded together in one-room homes. And when the same space is used for cooking, living and sleeping, the entire family is exposed to cookstove fumes. Cookstove fuel differs across classes, too. Poorer families burn crop waste or freshly gathered wood, both of which create more smoke than the dry wood used by wealthier families. In cities, Brauer says, richer people live in homes set back from busy roads, whereas those with fewer means are more likely to live near factories and highways.

Another pattern that researchers see over and over again is that those breathing more toxic air are also those who are most likely to experience societal stressors: poverty, racism, limited health-care access, and more. The combination increases their risk of disease. Researchers are only now beginning to tease apart how the chronic stress of discrimination makes

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Graphics by Miriam Quick and Jen Christiansen

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someone more vulnerable to the harms of environmental pollutants. "Social factors cause repeated chronic stress to the point that the body has a harder time defending itself against harmful exposures," Habre says. People who experience social discrimination, especially based on race or ethnicity, are "getting higher exposures, but they are also more susceptible to their harmful effects."

Those breathing more toxic air are also those who are most likely to experience societal stressors: poverty, racism, limited health-care access, and more.

SEEKING SOLUTIONS

According to a 2022 *Lancet* study, air pollution caused about 6.7 million premature deaths in 2019, mostly in low- and middle-income countries. The nation with the highest number of these deaths was India. As part of its efforts to address this threat, in 2015 the Indian government issued a report that declared air pollution a national health concern. The report laid out a plan to start improving the nation's air, one of the first of its kind from a low- and middle-income country that, Sharan says, clearly states "it is exposure to emissions that matters, and therefore the people who are exposed to it that matter. Once you do that," he says, "then the question of equity comes up."

Creating policies that protect and prioritize the health of the most vulnerable is far from easy. In New Delhi, for instance, air quality is especially awful during certain winter months because of local weather conditions and emissions from agricultural burning as farmers clear fields for planting. To try to protect people's health, government authorities identified a set of steps they hoped would reduce toxic air exposure in the nation's capital. When $PM_{2.5}$ levels hit a certain mark, schools are to shut down so children can stay indoors. Vehicles must drive only on paved roads so as not to throw excess dust into the air. Private construction activities—at homes, malls, and other nonessential sites—must halt to protect workers and reduce the amount of fine particles flying into the air from cement grinding or stone cutting.

These steps can temporarily lower local $PM_{2.5}$ levels. But the cost of this reduced activity is most keenly felt by laborers who are paid daily wages. When schools are closed, children in poorer families are more likely to spend time outdoors than to remain inside next to an air purifier.

The people who can't afford to pay attention to the health risks of $PM_{2.5}$ are typically those most at risk. Thus, when a policy to reduce exposure to pollution threatens someone's income—or a country's economic development, for that matter—it's likely to fail.

Policies that work in rich countries can prove challenging to implement in low- and middle-income nations. Pallavi Pant, a global health researcher at the Health Effects Institute in Boston, points to car emissions as one example. In Kenya and Uganda, the demand for personal vehicles has led to an increase in imported used cars from countries such as Japan. These imported cars were designed to meet emissions-control standards for high-income countries, so they're built using the newest catalytic converters and other pricey pollution-reducing technology. But maintaining those cars, especially locating and paying for parts, can prove difficult in poorer countries. As a result, importers have taken to removing these components altogether before the cars are resold.

But top-down approaches may still be effective, Pant says. In India, for instance, regulators have begun to enforce more stringent standards for vehicle emissions, an approach shown to motivate the auto industry to find ways to meet those standards so it can continue selling cars. The results from this strategy are not yet visible, Pant says, because it takes time for an older fleet of vehicles to be replaced by new, cleaner ones. "We'll continue to see improvements in the vehicle fleet," she says.

The Indian government has also implemented the National Clean Air Program, a 2019 initiative that tasks state and municipal authorities with especially dirty air to find solutions to their pollution problems. The effort empowered local governments to begin acting on their own air pollution—perhaps most important by making funds available to implement solutions. "That has been a pretty pivotal shift," Pant says. "There's a lot more still to do, but it's a very useful first step in getting people involved."

By themselves, policies and laws cannot tackle the many ways that pollution from high-income countries is exported to low- and middle-income countries, Brauer says. Morals matter, too. He and his colleagues have quantified how outsourcing the production of consumer goods and services from the U.S. to Asia also outsourced the pollutants created by those factories. They estimated that, for the year 2007, about 22 percent of the 3.45 million deaths attributable to air pollution were a result of this reassigned burden of pollution. Although the data are now 15 years old, they still point to an important message. People should be "aware that some of what we are benefiting from has just been transferred to other people," Brauer says.

PROGRESS WITHOUT POLLUTION

In wealthy countries, air quality has been improved in part by new, expensive technologies that reduce pollutants but still rely on petroleum and other fossil fuels. Over the long term, however, such a strategy cannot fix the entire problem, because it does not minimize greenhouse gases, which also harm human health and are accelerating the climate crisis, Anenberg says. "We need to be simultaneously reducing greenhouse gases and air pollutants. And the way we do that is by burning less fuel, not putting on these technological control measures."

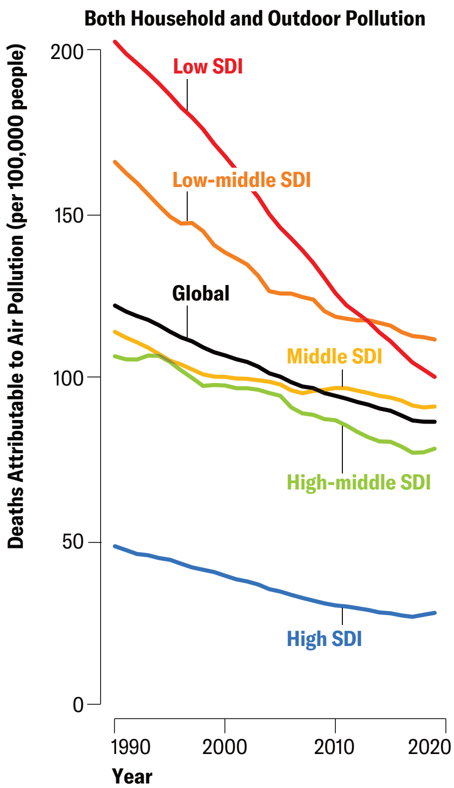
For decades industrial growth and the amount of pollutants in the air rose and fell together, Brauer says. Although pollution typically settles on the poorest, one exception is in countries with little industrialization, which still have relatively clean air. But as they industrialize and increase their reliance on fossil fuels, their air quality be-

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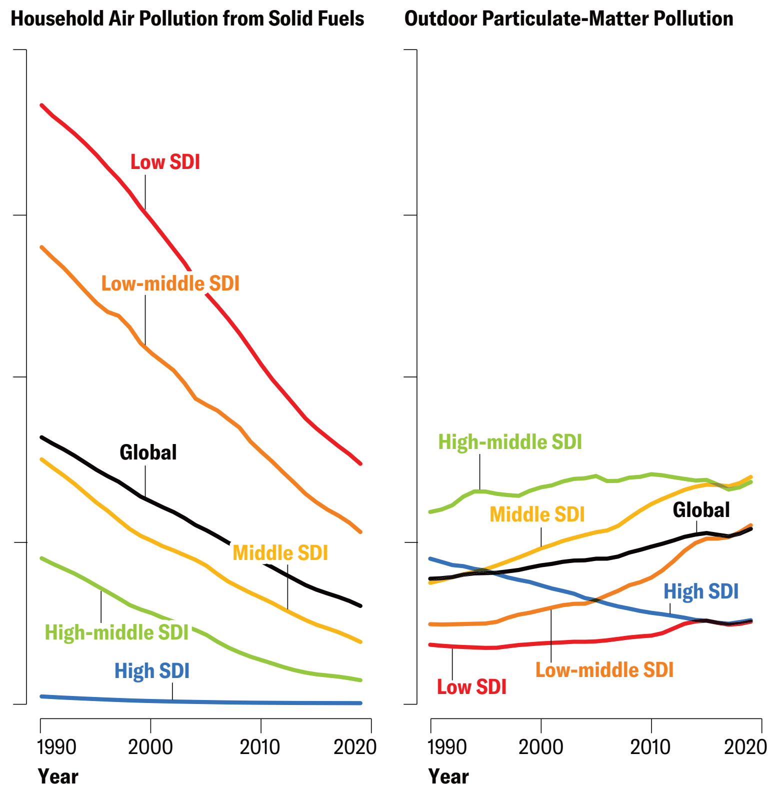
Death Rates Are Dropping, but Inequities Remain

Country-level data often mask local variation. But aggregate data can still reveal useful trends. The data here represent rates of death from air pollution sorted by sociodemographic index (SDI). SDI groupings incorporate income, education and fertility rates: in general, low SDI indicates a combination of low income, low education and high fertility, and high SDI indicates high income, high education and low fertility. SDI was developed by the Global Burden of Disease Study through the IHME.

Rates of death from air pollution are falling, although they remain much higher in countries and territories with low levels of income and education and high fertility rates.



A closer look reveals that the rate of death from indoor particulates has dropped sharply over the past few decades thanks to cleaner cookstoves. Mortality from outdoor particulates, however, is rising everywhere except in regions with high-SDI groups.



gins to worsen. "We've gone through this in high-income countries," Brauer says. "But many low- and middle-income countries are still in the earlier phases of this arc of industrial development."

Recognizing this problem has prompted some low- and middle-income countries to make changes. Rwanda, for example, has focused on off-grid solar-powered systems to provide electricity to rural areas. As of 2021, nearly 50 percent of the country had access to electricity, with much of that a result of solar power. India, too, is working to increase the amount of electricity it gets from renewable sources. In May the Indian government announced plans to pause proposals for new coal-burning power plants for the next five years and focus instead on renewable energy. "It's not a case that places get worse and worse and never improve," Brauer says. "We really do see improvement."

Such improvements happen when nations prioritize clean air and healthy citizens over short-term profits. Some high-income countries have introduced stringent policies to control pollution that have already led to measurable health improvements. In the U.S., one estimate found that laws controlling vehicle exhaust lowered mortality from traffic-related $PM_{2.5}$ by 2.4 times between 2008 and 2017. In London, the creation of an ultralow-emission zone in the central part of the city has reduced the amount of sick leave by an estimated 18 percent.

Another way to offset the health effects of pollution and simultaneously clean up some of our environmental mess is through planting trees. Exposure to $PM_{2.5}$ can significantly reduce blood flow to the brain, which influences stroke risk. But a study tracking more than 9,000 residents in Beijing found that living amid greenery mitigated this potential harm. And other research has shown that plants might also minimize heart disease risk from $PM_{2.5}$.

Today, armed with cleaner technologies and an awareness of toxic air's deadly effects, there's a chance that less industrialized countries could continue to choose progress without pollution. "This is not an either-or situation," Anenberg says. "We can do both of these at the same time." For clean and healthy air, this may be the only way to achieve true equity. ●

Jyoti Madhusoodanan is a science journalist based in Portland, Ore. She covers science, health and health equity for *Nature, Undark, Science,* and other outlets.

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Changing the Environment

These four researchers are highlighting environmental inequities and improving the health of their communities BY KATHERINE BOURZAC

One in four deaths worldwide can be linked to environmental conditions. Heart disease, cancer, chronic respiratory diseases, and more could be alleviated or even prevented by reducing environmental risks. Exposure to polluted water and air, flooding, extreme heat, and other dangers is driven in part by economic and racial discrimination, causing an unequal burden of disease. The political forces that drive this can be sweeping, but these four researchers are making a difference at a local level. They are attacking inequity, fighting historical wrongs, and helping to ensure a more equitable and healthy future.

KOFI AMEGAH

REVEALING AIR POLLUTION EXPOSURE



In 2015 Kofi Amegah traveled from Ghana to Switzerland for a World Health Organization meeting to share his work on how indoor air quality and nutrition affect the health of mothers and their children. After conferring with scientists from around the world, he realized Africa had a huge gap when it came to air pollution data. So the University of Cape Coast environmental epidemiologist decided to do something about it.

Rapid population growth and industrialization are creating a fast-growing problem, he says. Exposure to aerosol particles, specifically those 2.5 microns and smaller (called $PM_{2.5}$), increases the risk of heart disease, respiratory disease, and more. The WHO links this air pollution to 6.7 million premature deaths every year, 89 percent of which occur in low- and middle-income countries. As of 2019, 99 percent of the world's population lived somewhere with air quality poorer than that recommended by WHO guidelines.

Particulate matter in the air is an especially big issue in sub-Saharan African cities. To make a difference in people's health, Amegah needed local numbers. But air-quality monitors deployed by government-funded environmental agencies cost about $20,000 or more each, far beyond Amegah's research budget. Even in rich countries such as the U.S., these high-sensitivity monitors are distributed sparsely, obscuring inequities among neighborhoods.

Around the same time that Amegah went to the WHO meeting, relatively inexpensive air-pollution sensors began to hit the market. At just a few hundred dollars apiece, they are not as reliable as the more expensive regulatory monitors, but when carefully calibrated and combined into networks, they get the job done. Plus, their low cost makes it easier to distribute more of them to gather local data.

The Ghana Urban Air Quality Project started with one sensor in Cape Coast in May 2019, which Amegah paid for with his own money. The group he founded added two more in Accra by the end of its first year of operations. Today the team has about 60 air-quality sensors deployed across Ghana in the cities of Accra, Tema, Cape Coast, Takoradi and Kumasi. The project has also integrated 10 donated, regulatory-grade $PM_{2.5}$ monitors into the network to check the accuracy of the low-cost sensors.

Amegah established Breathe Accra last year. The nonprofit aims to identify air-pollution hotspots in Ghana's capital and to educate policymakers and residents about how to address them: governments can make regulatory interventions, for example, and schools can keep children inside on days when the air quality is bad. Amegah says he hopes Breathe Accra will act as "a blueprint other cities in Africa can follow."

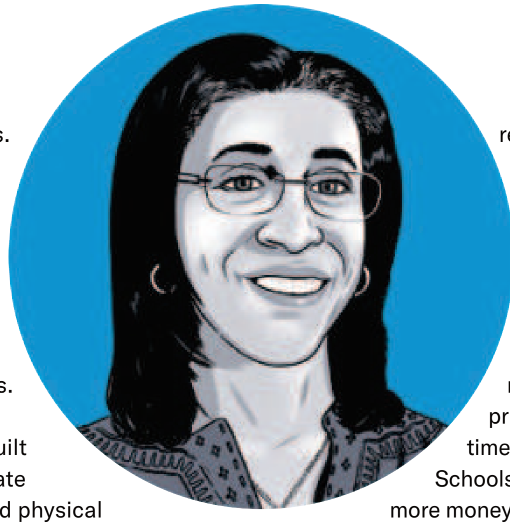
This sensor network is also advancing Amegah's epidemiology research, which centers on the health of street vendors, who are exposed to high levels of emissions from aging cars and two-stroke motorcycle engines. Within this community, he says, "the most vulnerable groups are women and children." Women spend up to 12 hours selling their wares and then head home to cook meals over coal- or wood-burning stoves, their young children with them. And the neighborhoods they live in are "the most polluted in the urban landscape," Amegah says, the air filled with road dust and smoke from burning trash.

Today Amegah has sensors mounted in schools, hospitals and traffic hotspots and is connecting the data to health outcomes for street vendors and children.

"Kofi's on the cutting edge of the science," says Richard E. Peltier, an environmental health scientist at the University of Massachusetts Amherst. "He's got the whole package. He's got the monitoring expertise, he's got the chutzpah to set up the monitoring network, and he's bringing it back to human health."

Illustrations by Joel Kimmel

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ERICA COCHRAN HAMEEN

RETROFITTING BUILDINGS FOR HEALTHIER SCHOOLS

As an architectural designer working in New York City, Erica Cochran Hameen was struck by how inequity had been built into the physical environment. Wealthy areas were lined with well-maintained public buildings, and schools in those districts had beautiful light and working doors. In lower-income neighborhoods, many buildings were disintegrating, and some public schools were far from parks and other green spaces.

Cochran Hameen began to question how built environments affect people, both physically and psychologically—and she wanted to quantify it. She returned to graduate school, where she began developing a set of more than 100 measures of indoor environmental quality. With her Ph.D. in hand, she started applying those measures to schools and probing how temperature, lighting, concentrations of various gases, and numerous other factors correlated with students' health and academic performance.

As an example, Cochran Hameen points to windows, which have a surprisingly strong effect on students' well-being and schoolwork. "You need a certain amount of daylight for your circadian rhythms," she says. That means large windows are better but only when they're also equipped with shades to mitigate glare and heat on sunny days.

These connections among the built environment, climate change, mental and physical health, and racial and social equity are complex and often overlooked. "Erica is working to make this [interplay] visible, tangible and meaningful," says Jenna Cramer, CEO of the Green Building Alliance in Pittsburgh. "Her research was early and groundbreaking." Talking about energy efficiency can sometimes feel abstract, but when people can see how energy use and environmental quality connect to children's learning and health, Cramer says, "it becomes a different conversation."

Cochran Hameen is now co-director of the Center for Building Performance and Diagnostics at Carnegie Mellon University, and her students are putting her metrics to work. They are assessing indoor environmental quality at schools and nonprofits in Pittsburgh and recommending upgrades based on their findings, some of which are relatively inexpensive—caulking holes, making windows operable and adding shades can make a big difference.

Other recommendations are pricier but pay off over time. Take energy costs: Schools in the U.S. spend more money on electricity than they do on books and computers. During on-site evaluations, Cochran Hameen found that some schools' HVAC systems set one temperature for the entire facility, so rooms with different uses, such as the gym and the math classrooms, were kept at the same temperature. When people opened windows or used space heaters to adjust their immediate surroundings, they wasted energy. Upgrading can save money and keep students comfortable and alert.

To make her resource-intensive evaluations accessible and affordable, Cochran Hameen has been collaborating with computer scientists at Carnegie Mellon. She wants to scale up her work by developing a sensor-laden robot that can navigate a building. "I want to show how architecture is beautiful but can also have a big impact on people," she says.

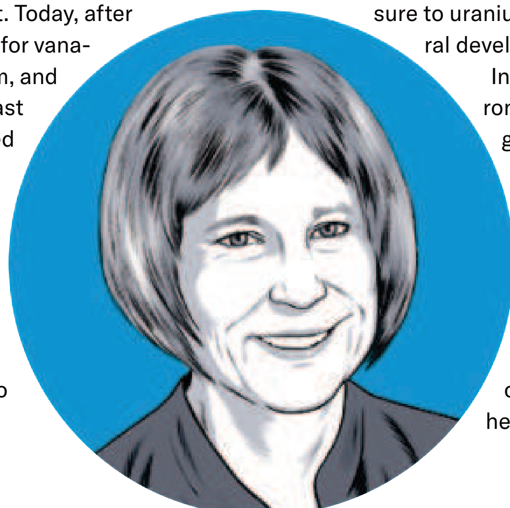
JOHNNYE LEWIS

CLINICAL TRIALS DRIVEN BY COMMUNITY PARTNERSHIPS

After Johnnye Lewis moved to New Mexico in 1989, she learned about the legacy of the land. She took a job as a consultant for Los Alamos National Laboratory, where she helped study the ecological and health impacts of nuclear research. That work, along with her involvement in community efforts to reconstruct historic radiation-exposure doses during the nuclear era, led her to start attending community meetings. She listened to residents discuss their concerns about the aftereffects of the atomic bomb, which was developed nearby, as well as ongoing health impacts from uranium mining on Navajo Nation land. It seemed to Lewis that scientists, politicians and members of Indigenous groups weren't using the same language to talk about these problems, and tribal members were paying with their health.

"I wanted to build a common language to move toward solutions," Lewis says.

In 1919 Congress permitted companies to excavate ore deposits on tribal lands with little oversight. Today, after decades of mining for vanadium, gold, uranium, and other metals, at least 160,000 abandoned mines remain in the western U.S. More than 500 abandoned uranium mines, along with 1,100 uranium waste sites, are on Navajo land, and people living there have been exposed for decades. At high doses, uranium in drinking water can cause kidney damage, and exposure to contaminated air can lead to lung cancer and other respiratory diseases. Preliminary results suggest that prenatal and early childhood exposure to uranium can impair neural development.



In her role as an environmental toxicologist and director of the University of New Mexico METALS Superfund Research Center, Lewis is connecting research with interventions that could immediately help people. Studies

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BERENDINA VAN WENDEL DE JOODE



PESTICIDE PROTECTOR

Anyone who works on or lives near a banana plantation in Costa Rica is subject to relatively high pesticide exposure. That's because farmers don't leave anything to chance. Every time a banana tree sprouts a leaf, it's newly vulnerable to fungal infection, so farmers spray fungicide from crop dusters and enclose growing fruits in plastic bags loaded with insecticide to deter bugs.

Berendina van Wendel de Joode has been working to change that. In the 1990s, as part of an internship, she moved to Costa Rica from her home country of the Netherlands to study farmworker exposure to the herbicide paraquat. She returned to Costa Rica in 2004 and has been at the National University of Costa Rica ever since.

Van Wendel de Joode focuses her research on how prenatal and childhood exposure to pesticides affects health and development in rural areas of the country. It's a complex problem: in the populations van Wendel de Joode works with, environmental-health dangers from pesticide exposure are layered on top of limited education, poverty and low food security.

One of van Wendel de Joode's projects is the Infants' Environmental Health Study, a large-scale study of 300 mother-child pairs in the Matina District of Limón Province. The project aims to determine which factors—such as how far a child's home is from a plantation or whether their parent works in agriculture—lead to higher chemical exposures and how that affects overall health and neurodevelopment. So far early results have revealed that women with evidence of fungicide exposure during pregnancy had infants with more respiratory infections and impaired neurodevelopment at age one.

Van Wendel de Joode's research led the Costa Rican government to provide clean water to a community whose groundwater is contaminated with pesticides and *Escherichia coli*. After her work with agronomists showed that plastic fruit bags were just as effective against insect damage when treated with mustard or without any chemicals at all, growers began phasing out the insecticide-treated versions.

Van Wendel de Joode is building maps of aerial-pesticide hotspots to show which ones are near inhabited areas. And her team has started a pilot program to test a play-based learning program for schoolchildren, including those with pesticide-induced neurodevelopmental delays.

The next generation of Costa Rican environmental epidemiologists is now being trained by van Wendel de Joode, says Ana Maria Mora, a physician and epidemiologist at the University of California, Berkeley's Center for Environmental Research and Community Health.

Mora worked with van Wendel de Joode and holds her former mentor in high regard. "She's passionate about Costa Rica and improving people's health," Mora says. "As a Costa Rican citizen, I feel incredibly grateful for what she's done."

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by scientists at the center found that arsenic and uranium can displace zinc in proteins that repair damaged DNA, which might increase cancer risk. Lewis's group is now testing whether zinc supplements could counteract this displacement and improve people's health.

Lewis tailored the trial, as she does with all her projects, to the needs of the people she works with. She and her team have consulted with the Red Water Pond Road community, whose tribal land is sandwiched between two abandoned uranium mines in New Mexico, to design multiple clinical trials. With community members' guidance, for example, the scientists built their preliminary zinc trial to include both elders and people with chronic conditions such as kidney damage—groups that have had the highest exposure to metals but are usually excluded from such clinical trials by researchers seeking "clean" data.

Community members in the Red Water Pond Road area also helped Lewis and her team design the Navajo Birth Cohort Study, which followed pregnant women and their babies through the children's first year of life, tracing their development, health and environmental exposure to toxic metals. The study, which began in 2013, has been extended and will continue to track the children as part of the National Institutes of Health's ongoing National Environmental Influences on Child Health Outcomes initiative.

Teracita (Terry) Keyanna, who grew up in Red Water Pond, says other scientists had informed them that the land was contaminated but then left without addressing the problem, something that has made it hard for residents to trust outsiders. Lewis has proved herself by working closely with those who have the most at stake. She "has developed that rapport with the community, and we trust her," Keyanna says. "It's taken a long time to do that."

Lewis started out in community engagement, working on recycling and food co-op projects before returning to academics and specializing in toxicology. She says her background and her recognition of the interconnection between the environment and human health have helped her work with Indigenous communities. They, in turn, have helped her improve the science. "Science is a special training I have, but it should just be one piece coming to the table," Lewis says.

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A Growing Fungal Threat

Valley fever hits outdoor workers disproportionately hard

BY ASHLI BLOW

Farmworkers in California's Central Valley know that when the tule fog settles over the ground after a heavy rain, some of them are about to get sick. Within a few weeks of the dense fog's arrival, many of the laborers grow tired and develop headaches and fevers. Each time, those who have evaded illness wonder whether they will be next. Experienced farmworkers expect this affliction, but when Rosalinda Guillen arrived from Washington State 25 years ago, she had never seen anything like it. She watched, helpless, as other farmworkers coughed and tried to catch their breath.

That was the first time Guillen, a seasonal farmworker and agricultural justice leader, heard the term "Valley fever." The disease is caused by two species of shapeshifting fungus in the genus *Coccidioides,* both of which flourish when exposed to moist springs and arid summers—like those in the San Joaquin Valley, where the fever got its name. Guillen had not encountered such a thing in her home state. But because of drier landscapes and warming temperatures, the fungus's range appears to be spreading.

No one knows for sure whether wind is moving *Coccidioides* north or whether it has been there undisturbed until now. But even as researchers have been discovering it in new pockets throughout the western U.S., many state health departments have failed to track it. What limited data exist indicate that 40 percent of cases become symptomatic, and among those the people most at risk of life-threatening disease are Latino, Asian and Native American people, who contract Valley fever at two to four times the rate of white people. That increased risk seems to be primarily attributable to their frequent exposure and long hours spent in dusty outdoor locations, although genetic variations haven't yet been ruled out.

Many of those affected lack basic health care, and some are afraid to seek medical help for fear of employer retaliation or even deportation. As a result, Valley fever is undersurveilled and underdiagnosed, and its study and treatment are underfunded. Research on the condition has remained limited, but it's clear that the disease disproportionately strikes people in the most vulnerable populations.

After decades of neglect, however, there's a new push at both the local and federal levels to find out more about the extent of Valley fever's threat. In addition, a small group of researchers is working to understand how to treat and even prevent it. That knowledge can't come soon enough, Guillen says: "All we really know is that farmworkers may already be sick."

GROWING EVIDENCE

Valley fever thrives both in dirt and in human lungs. After a heavy rain, the fast-growing *Coccidioides* spreads through the wet soil like mold through bread. When it dries out, its spores mingle with dusty topsoil and can be inhaled as airborne pathogens. Once they're in the lungs, those spores take on a wholly different form, each morphing into a reproductive cell in which new spores multiply. The full cells burst within five days, releasing spores that travel throughout the body. The fungus can cause coughing, fevers, body aches, fatigue, rashes and appetite loss. In up to 10 percent of those infected, some symptoms can last for years. The Centers for Disease Control and Prevention report that about 200 people die from the disease every year.

Bridget Barker, a mycologist and geneticist at Northern Arizona University, has spent her decades-long career figuring out how to detect *Coccidioides* and understand its role in the larger ecosystem. She and her team designed a probe to extract it from the soil so they can analyze it. Their research has revealed the fungus's resilience: *Coccidioides* needs moisture to grow, flourishing when the rains arrive, then stagnating when the ground dries up again. Its spores remain in the topsoil, where they can survive for years.

Barker and others refer to this process as the "grow-and-blow" cycle: once the fungus stops growing and becomes dehydrated, wind picks up the spores and carries them to new areas. This may be one way *Coccidioides* has expanded into the Pacific Northwest from the southwestern states, such as California, Arizona and New Mexico, where it is endemic. Researchers at the University of California, Irvine, predict that if warming trends continue and droughts persist, Valley fever could eventually stretch as far north as the U.S.-Canada border and as far northeast as North Dakota.

Amanda Gomez-Weaver, a doctoral student in environmental health sciences at the University of California, Berkeley, has been investigating the correlation between climate-influenced dust exposure and Valley fever epidemiology. Previous research had indicated that spores can become airborne anytime dirt is disrupted, making people working in construction and agriculture particularly susceptible. Gomez-Weaver has also found a strong association between Valley fever incidence and ambient dust, indicating that spores become suspended in the air and linger there much like other atmospheric particulates. This work has convinced her that anyone who spends most of their day in dusty outdoor areas in the western U.S. would need a *Coccidioides* vaccine to remain uninfected. To date, however, no vaccine is available for any fungal disease. A vaccine, Gomez-Weaver says, "would be the most powerful tool in our arsenal."

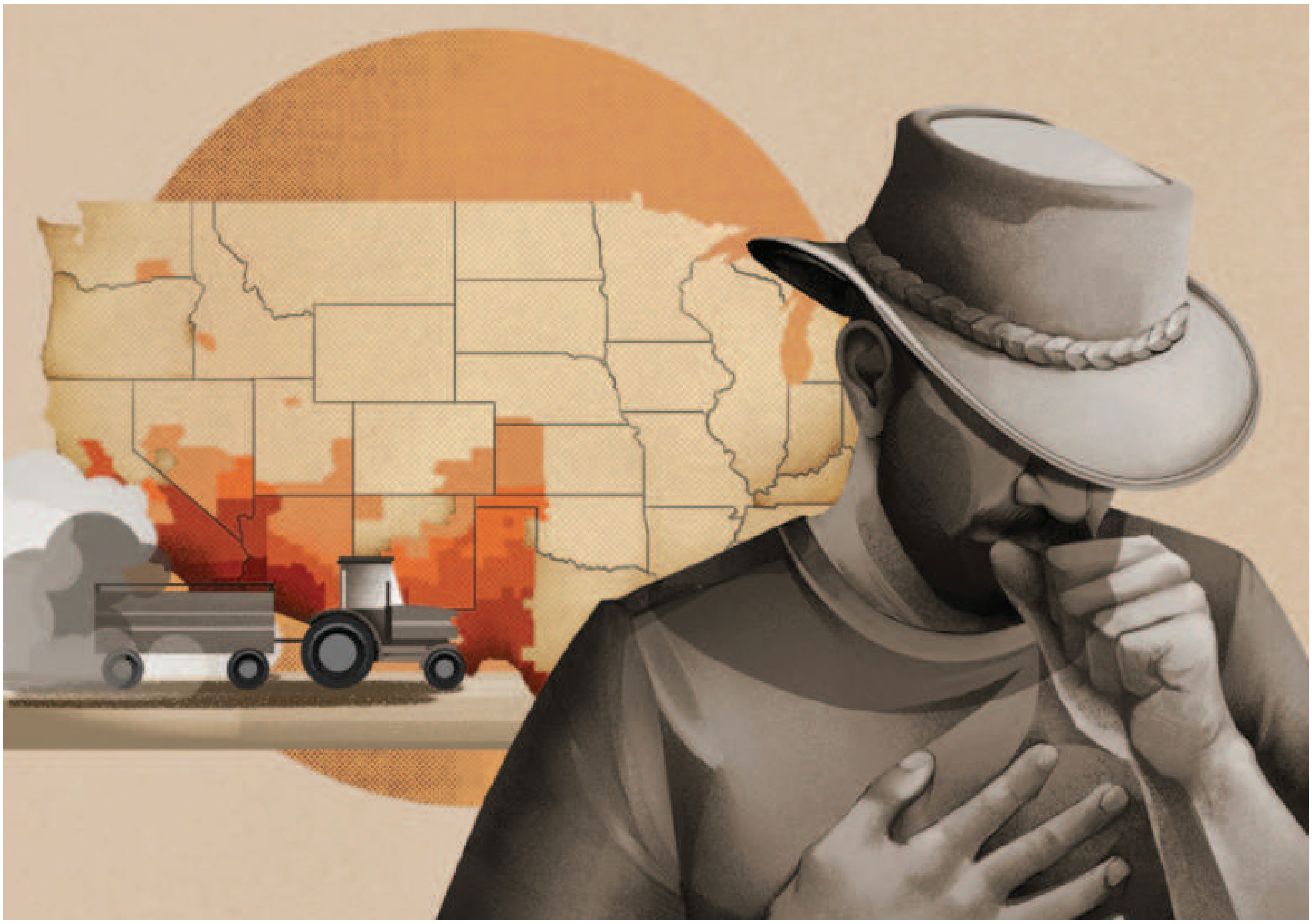
THE DATA GAP

Valley fever's mortality rate is about one death per 1,000 infections, according to infectious disease physician John Galgiani, director of the University of Arizona's Valley Fever Center for Excellence. It doesn't need to be so high. There are medications to treat it, but patients often receive incorrect diagnoses.

Physicians and other health-care practitioners who work where Valley fever is prevalent often don't know to test for it, because there's a general lack of awareness about the disease and because its symptoms can be mistaken for other respiratory illnesses, such as pneumonia. Patients usually end up with antibiotics or other medications that kill bacteria but not fungi.

The CDC estimates that only one in 33 cases is reported and has suggested that hundreds of thousands of infections have probably been missed over the past 10

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years. Because the organization does not mandate that public health departments report Valley fever—only 26 states have submitted case numbers—it has no data at all from some states where the fungus is endemic, such as Texas and Idaho.

Farmworkers and laborers who toil in the dusty outdoors, most often people of color, have been trying to get the attention of state and federal agencies for decades. “If something is harming us,” Guillen says, “it’s hard to prove based on the way that data-collecting systems are structured.”

PROOF OF CONCEPT

To show that a vaccine could be effective protection against *Coccidioides,* Galgiani and his team started by focusing on an immunization for dogs with the infection. Dogs are vulnerable to the disease, too. Because they explore the environment through their noses and can inhale large quantities of fungal spores in a short time, they contract Valley fever more often than humans do, and their symptoms can be more severe.

The canine vaccine Galgiani helped to develop has already proved itself. It uses attenuated live spores of *Coccidioides* that can’t reproduce but still prompt an immune reaction in the body. The response they elicit is so robust that a veterinary pharmaceutical company has licensed the rights to the vaccine and is seeking approval from the Department of Agriculture for its use in pets. Galgiani has now moved on to humans.

One potential benefit of a Valley fever vaccine is that it could be a one-and-done kind of thing—unlike those for influenza or even tetanus, which must be updated regularly. According to studies by microbiologist Deborah Fuller of the University of Washington School of Medicine, people who get Valley fever develop lifelong immunity. That, Fuller says, “is the golden egg.”

Fuller’s team is pursuing both DNA- and RNA-based vaccines, each of which would prompt the body to produce proteins that trigger an immune response. Fuller notes that any vaccine against *Coccidioides* would serve a greater purpose than just fighting Valley fever: it could allow researchers to understand immune response to other fungal diseases and provide insight into how to better treat such conditions.

Galgiani believes that if funding allows, a human version of his vaccine could be ready for approval within eight years. That funding may finally be within reach. After Valley fever’s annual incidence surpassed 20,000 cases in 2019, two congressional representatives—Kevin McCarthy of California and David Schweikert of Arizona—called on the National Institutes of Health to make a substantial investment in Valley fever research. Last year the NIH complied, dedicating $4.5 million in funding to the cause.

It’s about time, Guillen says. She has seen how agricultural workers are made vulnerable just by the dint of their surroundings, toiling in jobs that expose them to agrochemicals, dehydration, extreme heat, and more. Growing up in Washington State, working in the fields herself starting at age 16, she never had to worry about Valley fever. But now she’s watching it creep in and threaten the people she’s tried so hard to protect. She’s fighting to make sure some of the most invisible workers are seen. ⬢

Ashli Blow is a journalist who covers environmental science and justice with a focus on climate adaptation.

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A Fanged Crisis

More people die from snakebite envenomation than from almost any other neglected tropical disease

BY CASSANDRA WILLYARD

Inside a two-story brick building, not far from the orchids and iguanas of the botanical garden in Medellín, Colombia, wildlife technician Jorge Asprilla demonstrates how to extract venom from a snake. First, he uses a metal hook with an extended handle to snag a five-foot-long pit viper. Then he has to grab its head without getting bitten—a skill he has perfected after working for more than 25 years with dozens of venomous snake species.

Soon Asprilla has the snake's spade-shaped head firmly in his grasp and its muscular body pinned between his legs. The snake in his grip is known locally as a mapaná, and this species is responsible for most of the snakebites in Colombia. Asprilla has been bitten twice since he started working at the University of Antioquia's serpentarium, but he isn't one to elaborate on the experience. "*Duele mucho,*" he says. ("It hurts a lot.")

Venomous snakes bite about 5,000 people a year in Colombia; between 20 and 40 of those bitten die from their injuries. And although Colombia has the ability to produce and distribute antivenom—the antidote for venomous snakebites—about 20 percent of the victims who need antivenom don't receive it. Globally as many as 2.7 million people are envenomed by snakes every year. Of these, up to 400,000 are permanently disabled, and estimates suggest that 81,000 to 138,000 die. Venomous snakebites may receive less attention from health organizations than contagious viruses and bacterial infections, but their toxic effects make them one of the deadliest neglected tropical diseases.

Asprilla moves the hook into the mapaná's mouth, just behind its pallid, curved fangs. As he massages the snake's head with his hand, a bead of gold venom oozes out of a tooth. This liquid is responsible for both life and death: it can kill a human in days, and it can be used to produce the antivenom that might save someone by counteracting a venomous bite. Despite the existence of such antivenom, however, people continue to die. Asprilla's work is part of a project aiming to change that.

Snakebites aren't limited to low-income countries. Australia, for instance, has more venomous snakes than nonvenomous ones. But because of lifestyle factors and access to health care, the country records relatively few deaths from snakebites every year. In many low-income nations, dangerous bites are a pervasive threat. Most people bitten by snakes live in poverty, many of them in rural areas far from good medical care. They are rice farmers who tend to their fields in bare feet, herders who walk their cattle in the bush, families who sleep on the floor in homes with abundant entry points for snakes and the rodents they feed on.

"These people, these farmers, are voiceless. They don't have any good representation," says Abdulrazaq Habib, an infectious and tropical disease doctor at Bayero University in Kano, Nigeria. For many victims, antivenom comes too late or not at all.

Exactly how many people are bitten, and how many of those people die, is difficult to determine. Official records often underestimate the incidence. Victims might die before they reach the clinic, or they might seek care from a traditional healer. Even those who do go to the doctor might not be counted. In many countries, doctors aren't obligated to report snakebites to the government. Estimates based on household surveys aren't always accurate, either. What is clear is that India and Pakistan bear the brunt of the impact. According to one estimate, in 2019 more than 75 percent of the people who died from snakebites globally were residents of those countries. In India, venomous snakes kill some 50,000 people a year. In the U.S., although 7,000 or 8,000 people are bitten by venomous snakes every year, about five of them die.



The mapaná, a species of pit viper, is responsible for most of the venomous snakebites in Colombia. Here wildlife technician Jorge Asprilla is preparing to collect mapaná venom to use for antivenom production.

Photographs by Juan Arredondo

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The World Health Organization, under pressure from some of its member states, added snakebite envenoming to its list of neglected tropical diseases in 2017 and, two years later, laid out a strategy for prevention and control. The organization aims to halve the number of deaths and cases of disability by 2030. But the world has made little progress toward that goal, which many experts believe is unrealistic.

On the surface, reducing snakebite deaths seems easy, says David Williams, a toxinologist who assesses antivenoms for the WHO. Dig a bit deeper, however, and the true complexity of the problem emerges. Not every country has the same variety of venomous snakes. Species with different toxins require different antivenoms. The world produces less antivenom than it needs, and production quality varies. The cost to manufacture the remedy is more than most patients can afford. And those bitten often live in remote areas where they can't access antivenom quickly.

The most intractable obstacle, however, is apathy. Snakebite envenomings are "the most neglected among the neglected," says snakebite expert Mohammad Abul Faiz, a retired physician and current president of the Toxicology Society of Bangladesh. Few politicians seem to care about solving the problem.

Ending the snakebite crisis will require education, cooperation, research and, most of all, money. Countries need to make the problem a priority, Williams says: "If they choose not to invest in [the problem], then, to be perfectly honest, it doesn't matter what the rest of us do. We will never change anything."

PRODUCTION WOES

Antivenom production today is a modernized version of a technique first used 120 years ago. Technicians inject minuscule quantities of venom into horses or sheep over several weeks, then harvest their blood and extract the antibodies—all of them. In most cases, Williams says, "What you're getting in the vial is not just antibodies that are specific to the venom of the snake but antibodies for all the other antigens that horse was ever exposed to."

Once the antivenom gets injected into a patient, some of those antibodies will bind to the various components of the snake venom and neutralize it. Because different kinds of snakes carry different toxins, the antivenom typically must match the species. The approach prevents venom from causing damage, but it can't reverse damage that has already been done, so it works best in the first couple of hours after the bite. That means a person must reach a treatment facility quickly, the facility must have the appropriate antivenom in stock, and a doctor must administer it. The system is labor-intensive, inefficient and littered with obstacles.

Antivenom production in Colombia has dwindled in recent years from three sources down to one. Colombia's National Institute of Health produces about 10,000 to 20,000 vials a year. That's not enough, according to calculations by Sebastián Estrada-Gómez, a toxinologist at the University of Antioquia who helped to create the antivenom company Tech Life Saving, a spin-off of the university and part of a biotech development firm called Tech Innovation Group. With help from an angel investor, Estrada-Gómez has started to produce antivenom just outside Medellín with his "crew": Diabla, Elisa, Margara, and more than a dozen other sleek, brown and white horses that are part of his antivenom production. The government provides liquid antivenom, but Estrada-Gómez is working to make a freeze-dried product that doesn't require refrigeration and has a longer shelf life.

THINK LOCAL

Sri Lanka, an island nation slightly larger than West Virginia, is home to about 100 species of snakes, roughly a quarter of which are venomous. Experts estimate that as many as 60,000 people there are bitten by venomous snakes every year, and 200 of those people die. The country gets nearly all its antivenom from India, the largest producer and exporter of antivenom in the world.

Indian antivenom targets the "big four" species of venomous snakes in the region: the Indian cobra, the common krait, Russell's viper and the saw-scaled viper. These four species account for most of the venomous snakebites in India. Sri Lanka also is home to all these snakes, but its most frequent envenoming is from the hump-nosed pit viper, for which no commercially available antivenom exists. Although its bites are rarely fatal, they can cause excruciating pain and swelling. In some cases, they can lead to kidney damage. Tissue death around the bite may require skin grafts or amputation. The



Erney Arboleda stands next to the coffee tree where he was bitten by a snake commonly known as an eyelash viper. He killed the viper to show physicians at the city hospital, an hour's drive away, what species had bitten him. After a local search for the antidote, he was treated three hours later, then kept under observation at the hospital for four days before being sent home to rest.

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bites are most severe in small children.

Complicating the problem even further, antivenom against the same species may not work equally well in different locales. Some evidence suggests that antivenom developed using venom from Indian Russell's vipers, for instance, is less effective against venom from Sri Lankan Russell's vipers.

In an ideal world, Sri Lanka would make its own antivenom. About a decade ago collaborators from the U.S., Costa Rica and Sri Lanka formed a partnership to do just that. A U.S.-based nonprofit called Animal Venom Research International helped to set up Sri Lanka's first serpentarium and train staff to extract venom. Sri Lankan technicians collected the venom and shipped it to the Clodomiro Picado Institute in Costa Rica, one of the premier antivenom production facilities in the world. The institute produced more than 3,000 vials of antivenom targeting five species, including the hump-nosed pit viper. Researchers at the University of Peradeniya in Sri Lanka then used those vials to launch a clinical trial. The trials are ongoing, and no results have been published.

But Kalana Maduwage, a physician and antivenom researcher who was part of the

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project, says that data showed just a single vial of the antivenom can neutralize hump-nosed viper bites. For Russell's viper bites, the antivenom seems to produce fewer allergic reactions than other available options.

The ultimate goal was to transfer the technology from Costa Rica to Sri Lanka. Maduwage even trained in Costa Rica to learn how to produce the antivenom. But when he got back to Sri Lanka, he and his colleagues couldn't get funding to push the project forward. The serpentarium still exists, and Maduwage, who is now based at the University of New England in Armidale, Australia, says the Sri Lankan government is willing to buy the antivenom if the country can produce it. But the team needs at least $10 million to build the production facility. He understands why investors might be hesitant. Antivenom is expensive to produce, and demand in Sri Lanka is limited, so it could take years to turn a profit, Maduwage says. "This is not an easy money-making project."

The lack of profitability is an obstacle not just in Sri Lanka but worldwide, says José María Gutiérrez Gutiérrez, a toxinologist and former director of the Clodomiro Picado Research Institute. The problem might be one that the market alone can't solve. Rather he says there needs to be greater involvement by the public sector, an approach that has worked well in Costa Rica. The Clodomiro Picado Institute, which is publicly funded, not only provides enough antivenom to meet Costa Rica's needs but also ships antivenom throughout Central America as well as to countries in South America and sub-Saharan Africa. The country has an abundance of venomous snakes but has managed to keep snakebite deaths low, with three or fewer a year.

COSTLY CURE

Bolstering antivenom production will address only part of the problem. The remedy must be not just accessible but affordable. It is often neither. In Nigeria, for example, a small and bad-tempered snake called the West African carpet viper is responsible for most of the country's bites. The government supplies antivenom free of cost, but there is not enough to help everyone in need. In 2017 the Nigerian government spent only $192,000 on its antivenom program, which is enough money to treat about 4 percent of the country's snakebites. To halve the number of deaths, as the WHO hopes to do, Nigeria would have to spend about 50 times that amount.

When free antivenom is not available, the cost to individuals can be prohibitive. The therapy runs anywhere from $60 to $150 per vial, and a patient might need more than one. Yet 40 percent of the Nigerian population makes less than $2 a day. Antivenom, Habib says, "is a catastrophic health expenditure." On top of that, patients must also cover the high cost of bite-associated injuries, which have to be treated at a hospital. Because carpet viper bites cause bleeding and tissue decay, some victims may need blood transfusions. Unluckier ones may need dead tissue sliced out of their wound or a limb amputated.

Because hospital costs are so high, many people try to avoid hospitals altogether. "Victims visit traditional healers first," Habib says. "It's cheaper and probably more accessible." It's also ineffective. The therapies these healers provide—sucking venom from the wound, applying tourniquets and offering charred animal bones called "black stones"—not only delay access to care but also can lead to additional medical complications.

Even when antivenom is accessible, obstacles persist. The therapy can cause life-threatening anaphylaxis or other allergic reactions because of horse proteins in the antivenom or contamination during production. The risk of a reaction can be 40 percent or more depending on the patient's susceptibility, the number of vials administered and the purity of the antivenom. In serious cases, doctors might have to provide adrenaline to counteract the reaction or even intubate the patient. When hospitals aren't properly equipped to deal with these complications, antivenom can kill.

Worries over these outcomes have made some doctors and nurses too nervous to use antivenom therapies. Ravikar Ralph, a physician at the Christian Medical College in Vellore, India, says that snakebite patients often travel from a remote area to their closest medical center for treatment. But given all the potential complications, it's not uncommon for physicians in these small clinics to doubt their ability to treat a snakebite and send patients to a larger hospital. One survey found that only a third of Indian health-care professionals knew how to correctly manage adverse reactions to antivenom. "Invariably what happens is that these patients are then sent off to larger hospitals," Ralph says. The resulting delay in treatment can be a matter of life or death.

The health-care workers' lack of trust in antivenom spills over into the general public. "If you invite the community to come to the hospital and you are not able to provide services, then why will they come?" Faiz says.

This fear and mistrust can be countered with education campaigns. When snakebite cases ballooned in Baringo County, Kenya, in 2018, Doctors Without Borders stepped in. The organization helped to train 200 health-care workers to manage snakebites and taught community members how to avoid bites and provide first aid for victims. Julien Potet, an adviser on policy for neglected tropical diseases at Doctors Without Borders in Paris, says that training, combined with better antivenom access, made a significant difference in Baringo County. It's only one example, Potet says, but it shows what is possible.

NEW ADVANCES

Snakebite envenomation may be one of the most neglected tropical diseases, but a growing number of people are paying attention and working from all angles to try to improve patients' outcomes. A variety of tools are moving forward, from tests to detect venom in the blood, to antivenoms that are easier to produce, to oral medications that could help even before victims arrive at the hospital.

In Sri Lanka, delayed care isn't a result of transportation difficulties or avoidance by doctors—people who have been bitten typically make it to the hospital within an hour. Once there, however, the country's snakebite management guidelines advise physicians to wait for a patient to develop signs of systemic envenoming, such as bleeding or kidney failure, to avoid caus-

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These powdered antivenom samples being developed by the company Tech Life Saving are shelf-stable for up to two years.

ing unnecessary side effects in case the snake was not venomous or didn't release any venom. (For some species of venomous snakes, roughly half of bites are "dry" bites with no venom.) "By the time the patient develops clinical features, organ damage has already started," Maduwage says. That's why he started working on a rapid bedside test to detect snake venom in blood. "I know how to develop this point-of-care device. I have the technology," he says. "It was hindered by finances and funding."

Researchers are also working on better antidotes. Snake venom consists of a complex concoction of toxins, made from dozens of different proteins and peptides. Monoclonal antibodies, which are lab-made antibodies produced in human cells, could be manufactured faster than antivenoms—in days instead of months—and could avoid some of the allergic reactions they cause. But monoclonal treatments are also pricey, and different combinations of antibodies would still be required for each snake species.

Ophirex, a California-based biotech company, aims to eliminate that problem and is pursuing a near-universal therapy. Because snake venom is such a motley combination of molecules, Ophirex is targeting what seems to be a common component: an enzyme called secretory phospholipase A2 (sPLA2) that occurs in 95 percent of snake venoms. In 2021 the company began a randomized, double-blinded, placebo-controlled study—the gold standard of clinical trials—to evaluate the safety and efficacy of its drug varespladib in people who had been bitten by venomous snakes. If it works, the therapy won't be a panacea, but it might buy people time to reach the hospital, Potet says.

These therapies will be valuable tools if they prove safe and effective, but approval is probably years away. "I've been hearing people talk about a universal antivenom for decades," the WHO's Williams says, adding that the process takes an inordinate amount of time. "We're still waiting to see it happen." Ideally, he would like to see more money and energy spent on improving existing antivenom production to enhance potency and safety. Jean-Philippe Chippaux, an expert on snakebites and former director of research at the French National Research Institute for Sustainable Development, agrees. Even if new drugs existed, hospitals would have to stock them, physicians would have to be trained to use them, and patients would have to be able to afford them, Chippaux says. "I don't mind researchers experimenting with new, shiny tools as long as they don't suck all the money out of the field," he adds.

In theory, reducing snakebite deaths—even by the amount suggested by the WHO—is not impossible. Better anti-

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venoms combined with community education, additional training for health-care workers and accessible medical care could save lives now. "In Bangladesh, in some hospitals the mortality is zero. So this is possible," Faiz says.

Even the best treatments, however, cannot begin to get at the root problem: poverty. "Neglected tropical diseases, by definition, thrive in rural settings or in disadvantaged communities," Potet says. "And snakebite is not an exception to that rule."

Preventing snakebites requires improving access to water, creating indoor toilets, using beds with netting, installing lighting and changing farming practices. Preventing deaths and chronic injury requires overall strengthening of the health-care system. "Until you do this and improve the social and economic status of those vulnerable sections of community, you really will not be able to tackle the problem of snakebites," Ralph says.

Back in the small brick building in Medellín, Asprilla returns the snake to its home, a glass vivarium that stretches from floor to ceiling. There are five snakes behind the glass, he says, although only three are noticeable.

"That's how the accidents happen—you don't see the snakes," Estrada-Gómez says. He has worked at the serpentarium with Asprilla for nearly two decades, but he's still reluctant to extract venom from snakes. The one closest to the door has wound its body into a series of S-shaped bends. "He's trying to accumulate energy to strike."

Estrada-Gómez finds working with horses much more rewarding. Most of the venom from the serpentarium goes to antivenom production at the farm near Medellín's airport where he works. His goal is to make sure Colombia has enough antivenom to go around. He can't solve every problem, but he can try to do something about this one.

"If you have a therapy that you know can work, and it can save lives, and you can produce it, why are people dying?" he says. "It's unbelievable that still people are dying." ●

Cassandra Willyard is a science journalist based in Madison, Wis. She covers public health, medicine, and more.



Toxinologist Sebastián Estrada-Gómez greets one of the horses he uses to incubate and produce antivenom.

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Islands of Illness

People of color and people in poverty disproportionately live in urban "heat islands" that take a severe toll on health BY MELBA NEWSOME

On a July day in 2021 that would become blazing hot, dozens of community volunteers gathered before sunrise at the Scrap Exchange, a reuse center for art materials in Durham, N.C. Using heat-sensing instruments, they fanned out along prescribed routes through the city, collecting data on air temperature and humidity in the morning, afternoon and evening.

The survey was part of a project by the National Oceanic and Atmospheric Administration to identify neighborhoods with really high summer heat levels. The results showed temperatures in historically Black neighborhoods were seven to 10 degrees Fahrenheit higher than in affluent areas where more white people lived.

Blocks in these Black neighborhoods had far less shady tree cover than other areas, which were leafy and green. "The 10-degree difference between locations within two miles of each other was surprising," says Durham County sustainability manager Tobin Freid. She added that the hot areas don't cool off much at night.

Treeless, breezeless tracts of hot concrete and pavement within cities have become known as urban heat islands. They are not healthy places. The consequences of extreme heat for the human body include cramps, exhaustion and heatstroke. It can amplify existing health conditions such as diabetes, asthma and chronic obstructive pulmonary disease, as well as push up rates of suicide, depression and premature births.

Extreme heat and heat islands are not unique to the U.S. Using data from 93 European cities, a 2023 *Lancet* study attributed more than 4 percent of deaths in those areas during the summer months to urban heat islands. The paper concluded that one third of these excess heat deaths could be prevented by a tree cover of 30 percent. Another analysis found that Kolkata and Mumbai in India and Manila in the Philippines were among the cities with the largest annual increases in extreme heat exposure worldwide between 1983 and 2016.

A growing body of research shows that people of color and people living below poverty levels are stuck in these islands, much more so than their white and wealthier counterparts. The disparity is most pernicious during the summer, when extreme heat waves are becoming more common and lasting longer. "The average person of color lives in a census tract with higher summer daytime SUHI [surface urban heat island] intensity than non-Hispanic whites in all but 6 of the 175 largest urbanized areas in the continental United States," wrote the authors of a 2021 study in *Nature*. A new analysis of 481 U.S. cities showed that the typical Black resident lives in air that is 0.5 degree F warmer than the average for their city. In contrast, the typical white resident lives in air that is 0.4 degree cooler than the city average. These patterns also follow wealth and poverty levels.

"It's expensive to keep your home cool, and it's even more expensive if you're in an urban heat island," says Jane Gilbert, who leads heat protection programs in Miami-Dade County in Florida. "About 70 percent of lower-income populations live in rental apartments with small wall units that landlords are under no obligation to repair or replace."

The patterns that led to urban heat islands are linked to redlining. In the 1930s the federal Home Owners' Loan Corporation began ranking a neighborhood's loan-worthiness based primarily on its racial composition and socioeconomic status. The policies reinforced segregation, exposed poor communities to industrial pollution, and limited investments in amenities such as trees and parks. A 2020 study of 108 cities in the U.S. found that 94 percent had elevated land-surface temperatures in formerly redlined areas compared with their nonredlined neighbors. The difference was as much as 12.6 degrees F.

Although redlining may no longer be practiced legally, its legacy remains. In the neighborhoods it affected, there are far fewer parks, homes are less energy-efficient, and pollution rates are higher. Structures tend to be more densely packed, which limits air circulation and drives up temperatures.

Cities without a history of redlining have similar disparities, says climate scientist Angel Hsu of the University of North Carolina at Chapel Hill. "It's due to something wider, more pernicious and systemic," she says. "It's environmental racism." Busy roadways and factories that heat the air are often placed in low-wealth communities of color, which lack the economic and political power to keep such things out.

As climate change makes the world warmer, dealing with urban heat islands is becoming a more urgent matter. In 2021 President Joe Biden launched a coordinated effort to respond to extreme heat. It included guidance for heat exposure limits from the Occupational Safety and Health Administration. (Many states have yet to adopt them.) The recent $1.2-trillion federal infrastructure package encourages investments in green construction and other practices to lower temperatures and improve air quality. And a 2023 federal grant program includes $1 billion to plant trees in urban areas.

Miami-Dade County has launched a multilingual public information campaign and started training community health-care practitioners and disaster volunteers to deal with heat-related illnesses. The county also purchased 1,700 energy-efficient air-conditioning units to install in public housing and is working toward a goal of 30 percent tree canopy. Atlanta and New Orleans created new zoning regulations and set sustainable-development goals that specifically address urban heat effects.

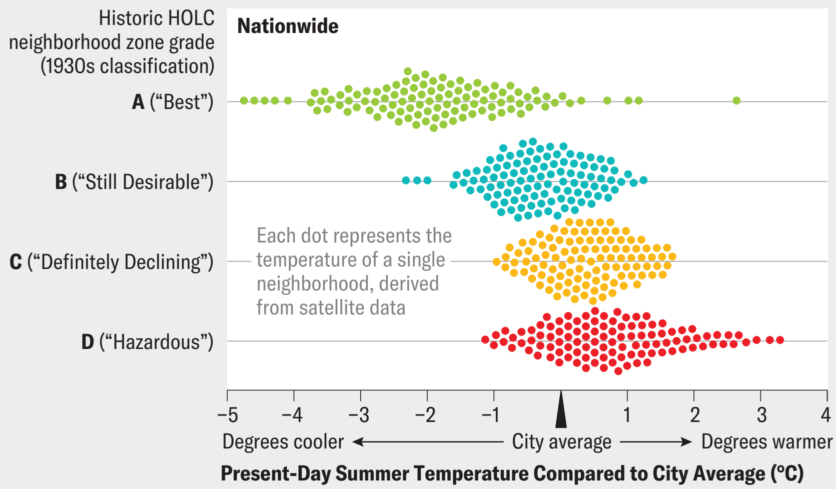
"We have a lot of great research that we need to mobilize into feasible and effective policy solutions," says Ashley Ward, a researcher at Duke University's Nicholas Institute for Energy, Environment & Sustainability. To build support, she recommends talking about issues that resonate across different political ideologies—such as health outcomes and their ties to where people live. ●

Melba Newsome is a 2023 Alicia Patterson fellow, reporting on climate displacement and people of color.

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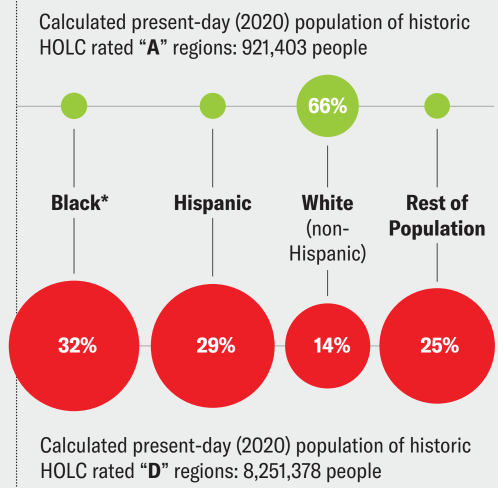
Hot Zones and Racial Bias

Today people of color live in hotter urban neighborhoods than do other groups. These areas have fewer shade trees and parks, have more houses with minimal air conditioning, and are closer to heat-generating large roadways. These patterns have roots in “redlining,” the refusal of banks and other financial institutions to invest in these neighborhoods. In the 1930s the Home Owners’ Loan Corporation (HOLC) began drawing maps that rated certain areas as bad for loans. The maps led to a more industrial, heat-retaining environment in some places. Summer temperatures in formerly redlined neighborhoods are now about 2.6 degrees Celsius (4.7 degrees Fahrenheit) higher than the average for their cities, according to a study in *Climate*. The difference is largest in the Southeast and the West.



WHO IS AFFECTED TODAY?

The ratings in the HOLC maps were based, to a degree, on the racial background of people in a particular neighborhood. Places with large Black populations were more likely to be rated “hazardous.” Currently those areas are likely to have the hottest city temperatures, and they have retained their historic population characteristics and a low rate of investment in improved conditions. In a 2022 analysis, places that had a “best” rating on the old maps were two-thirds white; places that had the lowest map ratings were 61 percent Black or Hispanic.



*Demographics labels reflect terminology used in the source.



Sources: “The Effects of Historical Housing Policies on Resident Exposure to Intra-Urban Heat: A Study of 108 US Urban Areas,” by Jeremy S. Hoffman et al., in *Climate*, Vol. 8; 2020 (*temperature data*); “Tracing the Legacy of Redlining: A New Method for Tracking the Origins of Housing Segregation,” by Helen C. S. Meier and Bruce C. Mitchell, in *NCRC Research*; February 2022 (*present-day demographics data*)

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Building Codes Save Money and Lives

As natural disasters become more common, updated building codes improve climate resiliency and save billions in repairs **BY THE EDITORS**



The aftermath of Hurricane Michael in Mexico Beach, Fla.

Johnny Milano/*The New York Times*/Redux

AFTER CATEGORY 5 Hurricane Michael slammed into Florida in 2018, the contrast in destruction was dramatic: homes built at or beyond state building codes still stood, whereas many built before stringent codes were simply gone.

Michael is one of a growing number of multibillion-dollar disasters in the U.S. that emphasize how crucial building codes are to protecting life and property. As climate change amplifies hazards, state and local governments must update them.

These standards are set, in part, by the International Code Council (ICC), an association of building safety professionals. After rigorous testing of building methods, postdisaster surveys and other research, experts develop a consensus set of model codes updated every three years. The codes apply to locally relevant hazards, from how high to raise a house to avoid flooding in Louisiana to how much shaking a building in San Francisco should be able to withstand. ICC officials tell us that the methods they recommend can be as simple as using certain types of nails that prevent roofs from blowing away during high winds.

These recommendations work. A 2018 study in *Land Economics* found that houses built after Florida adopted statewide building codes saw up to 72 percent fewer insured losses from wind damage. The nonprofit National Institute of Building Sciences found that for every $1 spent on conforming to codes, $11 in damage costs are saved.

But U.S. building codes are set by state and local governments, resulting in a confusing patchwork. A 2020 study by the Federal Emergency Management Agency (FEMA) found that 65 percent of counties, cities and towns have not adopted the most recent codes and that 30 percent of new construction is happening in places that have no code or have not updated theirs in 20 years.

Although San Antonio, Tex., has up-to-date codes, the unincorporated part of Bexar County has no codes whatsoever. Residents are often unaware their dwelling may not be resilient to winds, floods and other hazards, instead assuming the government has put proper safety standards in place.

As Anne Cope, chief engineer of the nonprofit Insurance Institute for Business & Home Safety, notes, we have safety standards for cribs, but "we have huge geographic swathes of the United States that have no safety standard for the shelter in which that crib is placed." (Look up your local code status at InspecttoProtect.org.)

Homebuilders and policymakers have said stronger codes would increase home prices. But no study has reliably shown that, and several have shown no effect. Moore, Okla., updated its codes after a 2011 tornado outbreak but did not see an appreciable difference in costs compared with nearby Norman, which did not enact an updated code. A sealed roof deck that keeps rain out when shingles are blown off may add to the initial cost of a new house, but it is far cheaper than repairing a roof and soaked floors, not to mention lowering insurance premiums.

Some officials, particularly in smaller jurisdictions, say they lack the funding or personnel to staff a building code enforcement office. To overcome this hurdle, communities in Texas use cooperative agreements with larger cities, and Pompano Beach, Fla., contracts with private engineering firms.

States must also provide incentives, such as grants for homes that meet certain standards. Alabama gave homeowners grants to build wind-resistant roofs, and they emerged largely unscathed from 2020's Hurricane Sally. Homes without such roofs were covered in blue tarps.

The federal government—which has limited means to influence building codes—must tie relevant state and municipal funding, such as predisaster mitigation grants, to having up-to-date building codes. It should also provide more funding for jurisdictions to meet hazard-resistant codes, in addition to energy-efficient ones.

It shouldn't take deadly hurricanes, tornadoes or floods for governments to decide to adopt strong building codes. These measures are part of climate resilience, good fiscal planning and common sense. They should be in place before disaster strikes.

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Cosmic Humility

Studies of worlds beyond our solar system could reveal just how significant Earth and its denizens really are BY MARIO LIVIO

WHEN NICOLAUS Copernicus proposed in 1543 that the sun was the center of our solar system, he did more than resurrect the "heliocentric" model devised by Greek astronomer Aristarchus of Samos. He took humanity down a peg. The ensuing "Copernican principle" tells us that we are nothing special. Earth is just another ordinary world revolving around an ordinary star.

Scientific revelations in the centuries that followed have only underscored our mediocrity. In the mid-19th century Charles Darwin realized that rather than being the "crown of creation," humans are simply a natural product of evolution by means of natural selection. Early in the 20th century Harlow Shapley showed that the entire solar system lives in the Milky Way's sleepy outer suburbs rather than the comparatively bustling galactic center. A few years later Edwin Hubble demonstrated that even our galaxy is unexceptional—one of many bundles of stars, planets, gas and dust. Estimates put the total number of galaxies in the observable universe at a staggering trillion or more.

Within the Milky Way, roughly 20 percent of sunlike or smaller stars harbor an Earth-size world orbiting in a "Goldilocks" region that is neither too hot nor too cold for liquid water to persist on a rocky planetary surface. At least a few hundred million planets in our galaxy may be habitable. With each advance in our knowledge, our existence is reduced to mere cosmic flotsam.

Mario Livio worked for 24 years with the Hubble Space Telescope and is a fellow of the American Association for the Advancement of Science. Livio is also author of seven popular science books, including, most recently, *Galileo and the Science Deniers* (Simon & Schuster, 2020).

Increasing numbers of physicists have begun to suspect—often against their most fervent hopes—that our entire universe may be but one member of a mind-bogglingly huge ensemble of universes: a *multiverse*. Interestingly, though, if a multiverse truly exists, it suggests a limit to Copernican humility. Many researchers speculate that random chance rather than fundamental laws sets the values for some of the three dozen physical constants that shape our reality. That is, the density of the "dark energy" that drives the universe's accelerating expansion or the ratios of masses of subatomic particles can take drastically different values in different parts of the multiverse. Moreover, the so-called laws of nature may be no more than local bylaws governing our particular patch of the multiverse.

If the multiverse exists, odds are the laws and constants prevailing in any given universe would preclude life's emergence. If so, we inhabit a rare subclass of universes that allows for life. In other words, we—humans, our planet, our universe—may be special after all.

Our astronomical search for life beyond the solar system may tell us where the Copernican principle breaks down. Extrapolating from what we know about how stars are born, live and die—and how a subset of them host potentially habitable Earth-size planets—one can estimate the relative likelihood of life's emergence in the universe as a function of time.

Because low-mass stars are the most numerous and longest-lived, in the future life in the cosmos is much more likely to arise on a planet orbiting a low-mass star, such as a red dwarf, rather than on a planet orbiting a bulkier star akin to our sun. In other words, life on Earth appears to be very premature and rather special.

Many factors could inhibit the formation of the chemical building blocks of life. For instance, red dwarf stars tend to emit strong flares and stellar winds that could strip planets of their atmospheres, thwarting the environmental conditions and availability of precursors that life-creating chemistries need to percolate. Current and near-future astronomical searches for biosignatures in the atmospheres of exoplanets, which now focus on worlds around low-mass red dwarfs, offer valuable clues as to whether life can exist in such settings.

Each blow to the Copernican principle and our own perceived physical significance was a tremendous expansion in our knowledge. The Copernican principle teaches us humility, yes, but also reminds us to keep our curiosity and passion for exploration alive. ■

Is life common throughout the cosmos? Worlds orbiting red dwarf stars may offer vital clues.

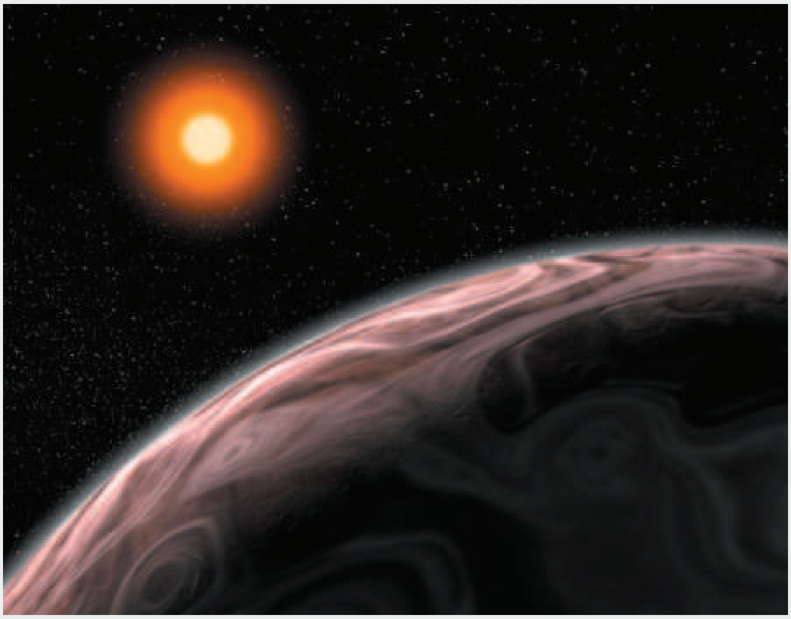


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Even Moderate Drinking Has Risks

Now research shows even a little wine is not benign. But risky enough for abstinence? BY LYDIA DENWORTH



WINE WITH DINNER is a lovely thing. I enjoy a glass or two, though rarely more. I have seen the terrible toll of alcohol use disorder and know the risks. Or I thought I did. I judged my drinking "moderate" and relatively benign.

A decade ago scientists and public health experts agreed with me. A drink or two a day was safely within most public health guidelines, and research even suggested that a little alcohol could protect against cardiovascular disease.

But earlier this year the World Health Organization (WHO) stated any amount of alcohol was dangerous. "There is no safe amount that does not affect health," the group declared. Canadian authorities redefined moderate-risk drinking as three to six drinks a week, down from a daily level of two for women and three for men. The U.S. now recommends a limit of one drink a day for women (that is, 12 ounces of beer, five ounces of wine or 1.5 ounces of spirits) and two for men. The message is clear: the chances of harm begin with the first drop.

This radical shift in thinking made headlines. Then my own doctor advised me to cut back. I was willing, but I wanted to understand what, exactly, I was risking with each sip of sauvignon blanc.

Previous health advice was designed to stop people from becoming alcoholics, says psychologist Tim Stockwell of the University of Victoria, a former director of the Canadian Institute for Substance Use Research, who has helped develop guidelines for three countries over 25 years. "It wasn't so much how you protect your body from cancer, liver disease, or losing a few months or even years of life expectancy."

Now a growing body of research says any alcohol raises the chance of premature death from a variety of causes. About half of cases of liver disease are attributed to drinking. Alcohol is also a potent carcinogen. It can cause cancer because it breaks down in the body to form a compound called acetaldehyde, which damages DNA. That damage can lead to at least seven types of cancer. Fifteen percent of breast cancers are linked to alcohol. And according to the WHO, half of cancers in Europe linked to alcohol are caused by "light" or "moderate" consumption.

These risks seem to cancel out evidence of alcohol's cardiovascular benefits, which was weakened anyway when researchers did more nuanced studies. The heart-protective theory was based on the finding that moderate drinkers had better cardiovascular health than both nondrinkers (by a little bit) and heavy drinkers (by a lot). But those studies lumped all nondrinkers together, including those who had quit because of substance use issues or illness. As a result, "abstainers" looked relatively unhealthy, and "moderate" drinkers, many of whom exercise and eat well, looked pretty good.

"The fundamental issue is who is in the comparison group," says psychiatrist Sarah Hartz of Washington University in St. Louis. In 2018, when Hartz and her colleagues compared thousands of moderate and very light drinkers (one or two drinks per week), the advantages of moderate consumption basically disappeared. Other studies got similar results. By 2022 the World Heart Federation stated that alcohol did not protect people.

Still, the increased risk for light and moderate drinkers must be considered in context. The Canadian guidelines estimate one additional premature death in 1,000 could be attributed to alcohol for those who have two drinks a week. That risk increases to one in 100 among people who have six drinks weekly. People take similar risks every day. The lifetime odds of dying in a car accident are one in 93, yet we still drive. We eat bacon. We even go skydiving. "We choose those things because we want to do them in spite of the known risks," Hartz says. "That's where alcohol needs to be lumped."

The choice is personal. (For people with alcohol use disorder, the option is abstinence.) People have long derived pleasure from alcohol. I am one of them, although my definition of "moderation" has shifted with the guidelines. I recognize that wine is not benign, and I have cut my consumption in half. But the occasional glass is a risk worth taking—for me. ●

Lydia Denworth is an award-winning science journalist and contributing editor for *Scientific American.* She is author of *Friendship: The Evolution, Biology, and Extraordinary Power of Life's Fundamental Bond* (W. W. Norton, 2020) and several other books of popular science.

Illustration by Jay Bendt

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Stay Sharp as You Age

Older people show significant cognitive benefits from learning new skills

BY RACHEL WU AND JESSICA A. CHURCH

IN MANY ADULTS, learning and thinking plateau and then begin to decline as early as age 30. People start to perform slightly worse in tests of cognitive abilities such as processing speed, the rate at which someone does a mental task. The slide becomes steeper in their mid-60s.

These changes are often ascribed to normal aging. But they may instead represent something more like the "summer slide" that some schoolchildren experience in academic progress during summer break. After formal education and job training end, many adults undergo years of reduced learning opportunities. Work by one of us (Wu) suggests that the cessation of learning is indeed a setback—but this decline can be addressed. A three-month intervention Wu and her colleagues designed enhanced participants' memory and cognitive flexibility so drastically that their abilities came to resemble those of adults 30 years younger by the program's end. And amazingly, they continued to improve long after the classes were over.

Rachel Wu is an associate professor of psychology at the University of California, Riverside. She studies cognitive aging and learning across the life span.

Jessica A. Church is an associate professor of psychology at the University of Texas at Austin. She studies cognitive development and learning in children and adolescents.

In this intervention, the researchers provided an encouraging learning environment to 24 older adults between 58 and 86 years of age. Before and after, they tested participants' cognitive abilities, including cognitive flexibility and working memory. (Whereas cognitive flexibility supports multitasking and attention, working memory helps people with short-term tasks such as dialing a phone number.) The older adults enrolled in at least three classes that met weekly, with each session lasting two hours, to learn three new skills. Course options included drawing, iPad use, photography, Spanish-language learning and music composition. Once a week the participants also discussed issues related to learning barriers, motivation and successful aging.

Over the course of the intervention, the participants' cognitive scores for memory and flexibility improved significantly. In a follow-up study, Wu and her colleagues discovered that participants had improved further: their cognitive abilities after one year were similar to those of adults 50 years younger. In other words, giving these seniors a supportive and structured multicourse routine seemed to eventually bring up their abilities to levels similar to those of college students.

The team is still investigating why cognitive scores continued to climb *after* the program's end, but one possibility is that the experience encouraged these adults to continue learning and practice new skills. To be clear, we do not think that formal education is the only or most important way to support learning. Our idea is to instead create enriched environments for older adults, especially for those with few resources, so they can increase both real-world skills and cognitive abilities over the long term.

If, as these studies indicate, interrupted learning is indeed a common feature of adulthood, many important implications follow. Older adults are often assumed to be on a downward slope with unrecoverable loss. "Use it or lose it," the saying goes. Our work suggests that we need to apply a more hopeful mindset and vocabulary when discussing older people. Decline, as we so often see it, may not be inevitable.

The question now is: How can society maximize adults' chances to keep learning? Educators and scientists know how to educate children and adolescents, and we can adapt that knowledge to pursue existing options and develop challenging, useful and inclusive learning opportunities for adults. Researchers who work on the developmental and aging ends of the life span should share perspectives and communicate findings with one another. Finally, societies could provide resources and paths toward lifelong learning—particularly for older adults who are underserved or disadvantaged—to ensure that everyone can benefit.

Let's shift the conversation about adults from staving off loss and decline, or merely maintaining what people have, to learning, growing and thriving. ●

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O. Usykov Institute for Radiophysics and Electronics, Kharkiv

The institute has been created as a center for theoretical studies, laboratory research, and mass production design. The generation, transmission, and reception of electromagnetic waves are comprehensively studied here.Ukraine's only microwave cryogenic complex is located in the institute, which is used for research on magnetic nanoparticles.

In March-April 2022, due to the Russian invasion and the battles on the northern outskirts of Kharkiv, the buildings of the institute were damaged by shelling. The photo shows employees on the territory of the institute, who, regardless of the war, stay in the country and continue their work.

Photographer: Valentyn Kuzan

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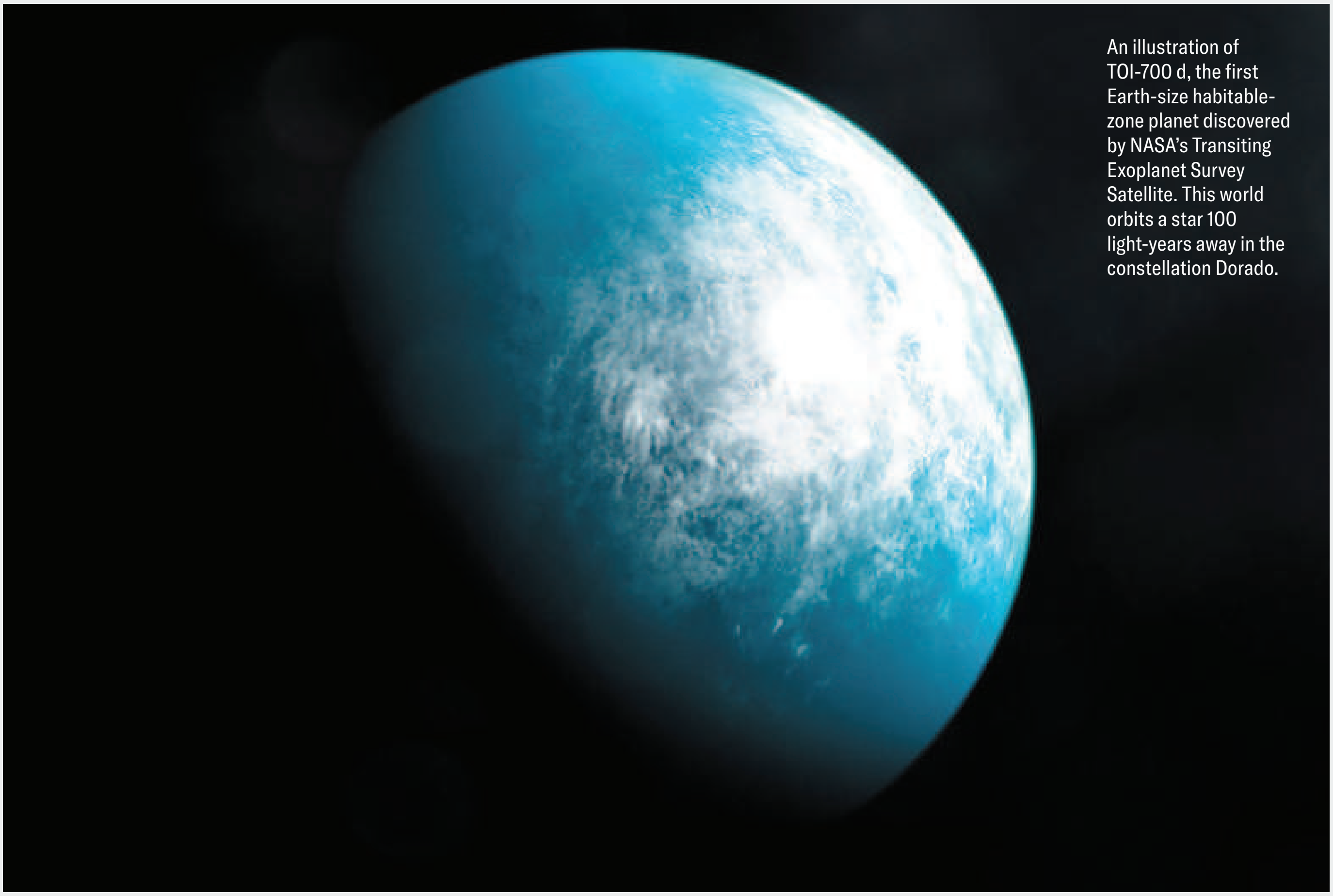
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An illustration of TOI-700 d, the first Earth-size habitable-zone planet discovered by NASA's Transiting Exoplanet Survey Satellite. This world orbits a star 100 light-years away in the constellation Dorado.

NASA Goddard Space Flight Center

The "Habitable Zone" Problem

When looking for livable planets, we should broaden our horizons BY PHIL PLAIT

ASTRONOMERS HAVE, SO far, discovered nearly 5,500 exoplanets—alien worlds orbiting alien stars—with more than 7,000 candidate planets still waiting to be confirmed.

That's a lot of planets.

We search for these distant worlds because we're curious and want to know what other planets are like. By understanding other worlds, we can better understand our own. But make no mistake, scientists are humans, and we want the answer to one of the biggest questions of the scientific age: Are we alone?

We may get an answer soon. Our technology is just on the cusp of detecting exoplanetary biosignatures, telltale signs of life such as molecules in planetary atmospheres that could indicate the presence of biology. Until then, though, it's useful to investigate everything we can about these planets and categorize them by their likelihood of supporting life.

A handy concept astronomers have for this is called the habitable zone. This is a region around a star where temperatures allow a planet to potentially harbor oceans, seas or lakes of liquid water on its surface. Too close and the stellar heat boils the water off. Too far and it freezes. Between these extremes, though, it could be just right. This middle-ground aspect is why some astronomers refer to it as the Goldilocks zone. (Although, to be honest, I've never cared for this moniker; I'd opt for the Baby Bear zone. Naming it after the person who broke into that ursine home and usurped all their hard-won food and property smacks of colonialism.)

As an idea, it's pretty useful. All life on Earth needs liquid water, and because we're unaware as yet of any other way life might occur, that's a good place to start.

Measuring habitable zones, however, isn't straightforward. Calculating the radiation a planet receives from its star is

Phil Plait is a professional astronomer and science communicator in Colorado. He writes the *Bad Astronomy Newsletter.* Follow him on Twitter @BadAstronomer

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easy; that depends on well-understood physics. The hard part is the planet itself. A dark planet absorbs more light and heats up, whereas a lighter-toned one will reflect more light and be colder.

A planet's atmosphere plays an even bigger role: if it's loaded with greenhouse gases, then the planet needs to be farther out from the star to be clement. Just look at Venus—our sibling world in many ways, similar to Earth in size and mass—to see how important that is. Lead would melt on our evil twin's surface because of its overwhelmingly thick atmospheric blanket of carbon dioxide. It's not exactly an Earth-like planet.

So on its own, finding a planet in a star's nominal habitable zone is no guarantee it will be, well, *habitable,* even if it's a small (and presumably) rocky world like our own. A lot more must be known, including whether it even has an atmosphere, what that atmosphere is composed of, and more. This problem is so complicated that astronomers argue over where our sun's habitable zone even starts, and we're literally inside it. What's more, the habitable zone might not be the only place where liquid water can exist in a solar system.

In the 1970s the Voyager 2 spacecraft flew by Jupiter's moon Europa and saw surface features that hinted at the presence of a liquid-water ocean underneath its frozen surface. We've since collected extremely compelling evidence of subsurface Europan liquid water kept warm by the moon's interaction with Jupiter's immense gravity.

Europa isn't the only ocean moon, either. In 2005 images from the Cassini spacecraft showed huge plumes of water erupting off the surface of Saturn's icy moon Enceladus. Probably generated by Saturn's tidal activity, similar to what warms Europa, these geysers point to the presence of immense pockets of subsurface liquid water, if not another ocean.

The concept of a habitable zone is woefully incomplete for the purpose of determining where life might exist. So is it time to kick it to the galactic curb?

Now we think there could be many such sub-ice oceans inside the moons of the solar system's outer planets and even in some of the larger objects orbiting the sun past Neptune.

In fact, we know of quite a few rogue planets meandering through interstellar space, which were probably ejected from their original planetary systems as the worlds there first formed and gravitationally interacted with one another. The ones we find tend to be gas giants even more massive than Jupiter. If they have icy moons, those, too, could be heated enough to have subsurface oceans. So *you might not even need to have a star* to have a habitable world!

To throw even more cold water on habitable zones, there are other liquids to ponder as well. Saturn's largest moon Titan is too cold to have liquid water on its surface, but Cassini observations in 2006 showed vast lakes of liquid methane there. Methane is a carbon-based molecule, so many of the ingredients for life are perforce there. Who knows whether there are alien fishies swimming in Titanic lakes a billion kilometers from the sun?

Needless to say, these are well outside the sun's quote-unquote habitable zone, yet it's possible that life may abound inside these prima facie frozen moons. Clearly, the concept of a habitable zone is woefully incomplete for the purpose of determining where life might exist. So is it time to kick it to the galactic curb?

Let's not throw out the extraterrestrial baby with the subsurface bathwater! Some years ago a team of planetary astronomers wrote that the term needs modifying and suggested it be replaced with "temperate zone." I think this idea is a fine one, still highly useful if we're looking for Earth-like planets, which, to be clear, *we are.* It might not include frozen moons of gas-giant planets or worlds where life as we *don't* know it may evolve, but as long as we are aware of these limitations, it's still handy. Renaming the concept could solve some things.

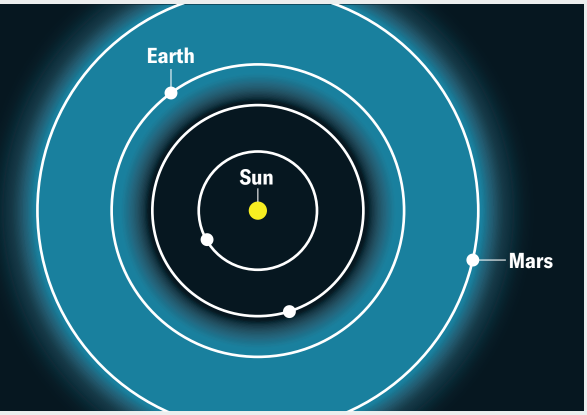
The habitable zone, even by any other name, was never meant to be an ironclad rule. It was always a guideline, an idea to inform astronomers that they might be onto something interesting when a planet is found in a certain spot. It's not a device for measuring potentially habitable worlds so much as a way to bookmark them for future observations.

It's easy to want to draw lines in the sand—a planet *this* far from its star is inhospitable, but a planet *that* far is great—but nature almost never behaves that way. It generally works on a spectrum, with fuzzy borders and even larger overlaps. It's always good to keep that in mind when reading about scientific discoveries.

A planet being in its star's habitable zone might not be sufficient, or even necessary, to make it habitable, but it's still a pretty good place to start when looking for life. We just need to make sure we don't stop there. ●

Our Solar System's Habitable Zone

Earth isn't the only orb in the sun's habitable zone (*blue*), the circumstellar region where sufficient starlight can support liquid water on a world's surface. Our lifeless moon lies within it as well, and by some estimates freeze-dried Mars does, too, showing the limits of the concept.



Graphic by Jen Christiansen

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What more can we do for patients? Taking action to deliver on our commitment

Many of the ideas, concepts, and approaches to achieving health equity we discussed in these pages last year remain as urgent as ever. At Takeda, we continue to believe that it's time to rethink health equity—and we've made progress. We remain committed to helping create equitable health care for all. Our health equity roadmap is centered on a core question Takeda has asked for more than 240 years, and one we use as the human yardstick of progress: What more can we do for our patients? We believe that's a question we'll continue to not only ask, but respond to, for the next 240-plus years.



The Center for Health Equity and Patient Affairs is one part of our health equity roadmap. Sitting at the intersection of research and access, it's intentionally structured as a Center of Excellence to provide essential services, programs, and frameworks that help Takeda build sustainable, physical, and intellectual infrastructures intended to address health disparities and inequities as a business strategy. While we may not have all the answers, asking questions fosters new ways of thinking and novel solutions that put us on the right path toward advancing health equity.

As we strive toward a more inclusive health ecosystem, it's important to look at the key learnings we've identified and modify our core principles appropriately. We must remember to evolve and apply our findings to future work so that companies and the industry benefit as well.

TERMS AND DEFINITIONS MATTER

It's clear that there's often a conflation of terms being used interchangeably: health equity (HE); diversity, equity and inclusion (DE&I); equality; corporate social responsibility (CSR); environmental, social and governance (ESG); and diversity in clinical trials—among others. But these concepts don't mean exactly the same thing: health equity, for example, targets systemic factors that lead to inequity and calls for different strategies. We have to identify how each of these approaches plays a part in advancing health equity. If we just use them as synonyms, we miss an opportunity to develop the most appropriate mix of strategies to the multifactorial problem of health inequity.

ADDRESSING HEALTH INEQUITIES IS NOT A FAD

The social determinants of health (SDOH)—the root causes of health inequities—are intertwined. Your education, economic stability, neighborhood, and social and cultural environment impact your understanding and opportunity to engage in healthy behaviors (**Fig. 1**). These factors can also limit access to appropriate resources to live your healthiest life. They make up our personal ecosystems and are often barriers to receiving quality care. This isn't a surprise, but a reminder of how crucial it is to address health inequities—for us and future generations.

Although these issues run deep, this hasn't paralyzed us at Takeda from continuing the journey to tackle health inequities. It has become apparent that it will take all of us working together to advance health equity. In fact, these challenges inspired us to do even more.

HEALTH EQUITY IS A MORAL IMPERATIVE AND BUSINESS STRATEGY

While many agree there's a pressing social need for addressing health inequities,

Factors that Contribute to a Person's Health



Source: Institute for Clinical Systems Improvement, Going Beyond Clinical Walls. Solving Complex Problems (October 2014)

Figure 1. The social determinants of health are the non-medical factors that can influence a person's well-being and health outcomes.

the business case is equally as robust. For Takeda, advancing health equity will allow us to deliver our innovative medicines and therapies to more people and communities that need them. Driving health equity forward continues to be critical to our mission of providing 'better health and a brighter future' for all and making that a reality. That's why Takeda was among the first of 39 companies to sign the Global Health Equity Network Zero Health Gaps Pledge at the World Economic Forum Annual 2023 Meeting in Davos. We agreed to ten key action commitments to embed health equity in our business strategy, operations, and investments. Our pledge at Davos reflects a commitment our company had upheld long before then, one grounded in our understanding that advancing health equity begins within the walls of our company and how we operate as a business.

Fundamental to making health equity a business priority is centering the voice of the patient and ensuring their diverse needs are incorporated into our business. For us, that means believing everyone deserves access to the care and medicines they need. This begins at the discovery phase and continues throughout commercialization and lifecycle management. What good are our medicines if patients can't access them? We aim to understand the diverse needs of patients and the communities in which they were born, grow, live, and work. This perspective equips us to create more inclusive practices and innovative medicines that better reflect what and how patients want and need to engage with health care. Our patient-centric approach encourages every group across our global organization to envision how addressing health disparities and inequities can help our employees, the patients they serve, and the company.

ASKING OURSELVES "WHY" TO HELP IMPROVE HEALTH OUTCOMES FOR ALL

Over the years, many companies have learned that listening closely and building trust with patients are critical ingredients of good care management and delivery. That's a key goal for us. We aim to treat the whole patient, using a customized approach that they can understand and adhere to, and that can deliver care close to where they live or work as they move along their health journey. We know that not every patient is the same clinically—not every patient responds to the medicines, therapies, or information the same way. Listening and learning will help us better understand not only what inequities are and where they exist, but why. Ask our team; they'll tell you our favorite question is 'why'. If we can understand the 'why' from the perspective of the patient, community, and their ecosystems, we'll be better equipped to provide people with the personalized care they need.

The importance of active listening. Regardless of the industry that you're in, achieving health equity calls for actively asking, listening, learning and then taking action, with an ear to the community and through ground-up strategic approaches. What resources do our local partners need to create more equitable communities and how can we provide access to our products for all patients regardless of where they're born, work, live, grow, or age? What about those who live in remote areas or lack health insurance? What do patients and communities believe is the best way to tackle health disparities? What's the next thing to do, then the next? What do our patients have to say about the plan? How do we make it sustainable? How are we measuring impact? These are some of the questions we use to guide our work and our partnerships because we know listening, learning, and co-creating can help provide positive impact to communities and to Takeda.



Needs first, then co-create

"We always start with the community identifying the need, no matter how basic or big. We don't say, 'We're going to give you this.' That's a very colonialistic perspective, right? We always listen, learn, and co-create—that's the order we start in. We then look for a way to ensure we are incorporating the learnings into our work, creating a path to make it sustainable, and educating, inspiring, and empowering others. All of our partnerships have started that way."

Charlotte Owens, MD

It's important to use data to understand not just what's happening to our patients, but 'why' so we can truly measure how their health has improved. Gathering the data and infusing these considerations into the way our industry works also helps enable us to deliver better access to health for patients around the globe. We need to begin looking at data beyond the numbers and activities. Once we do, we'll see it's about the impact—the true measurement of whether something is working or not.

At Takeda, we're designing metrics that measure impact and value at the community level—impact and value that matter to the patients and people we serve. These metrics are designed to uncover gaps in care and assess barriers to care. This approach creates a sustainable framework—from drug discovery through delivery—that helps shape our future work, collaboration, and efforts.

MOVING THE NEEDLE WITH GLOBAL PARTNERS

Health inequities are too vast and too multifactorial for any single entity to solve alone. That's why Takeda continues to believe in partnerships that bring together the private and public sectors, as well as non-governmental organizations, with shared interests. They are instrumental to advancing health equity. We need multifactorial approaches to the multifactorial problem of health inequity. Our partnerships bring together a diverse mix of resources and civil and governmental expertise to create reciprocal social impact—impact that makes the world better and allows everyone involved to benefit at the same time.

We seek partners that will assist in providing tangible and sustainable impact at three levels: for the communities and patients we serve; our company; and for future generations to come. It's our goal that all our partnerships educate, inspire, and empower all to be agents of change in their communities, regardless of their environments.

- In November 2022, Takeda partnered with Discovery Education on a three-year science, technology, engineering, and mathematics (STEM) education initiative, Better Health in Action: From Classroom to Community. Discovery Education is the worldwide edtech leader. The program is designed to empower young people to understand the principles of health equity and to identify health inequities in their communities through interactive, research-based learning experiences. It provides a suite of free, comprehensive digital resources for educators, students, and families with children in grades 6 to 8 (ages 11 to 14) and teaches STEM skills. It also introduces them to career opportunities and role models in life sciences. This first-of-its-kind program with Discovery Education is available to Discovery Education's audience of 4.5 million educators and 45 million students in more than 100 countries. The Better Health in Action program also expands global access by making our family guide and materials available in multiple languages.

- We're proud to be partners with Springer Nature and are continuing to roll out several initiatives including the global health equity Nature Café, an eye-opening docuseries of extraordinary people doing extraordinary work to combat inequities, and the *Innovations In* publication series. The newly launched Inclusive Health Research awards are designed to celebrate and support individuals and institutions that are driving more inclusive approaches to health research, and, in doing so, are promoting a future of greater health equity globally. These awards spotlight innovation and best practices in inclusive health research that have been influenced by engagement with affected communities and their expert representatives. The awards also aim to build a library of shareable case studies of new ideas and best practices that demonstrate the progress being made to advance global health equity.

- Takeda has partnered with Surgo Health, a technology company headquartered in Washington, D. C., to establish a multi-country social and cultural vulnerability index embedded into Surgo's Socio-Behavioral Intelligence Platform to provide insights that our

Keep asking questions. In our efforts to do better and achieve our health equity goals, here are some of the questions we are asking across all stages of our work, from developing new drugs and vaccines to getting them to the people who need them: How are we engaging, empowering and elevating patients from all communities to guide our research and development? How are we responding to patients' needs in our efforts to increase diversity across our clinical trials? How are we communicating the findings of clinical trials with patients in meaningful and understandable ways? While we may not have all the answers, surfacing the right questions invites solutions.

global teams can leverage to identify vulnerabilities, and the underlying reasons for them. This will help us better customize our approaches because we gain a deeper understanding of the patient and their community.

- In 2022, Takeda launched its De Novo Initiative, which focuses on helping people to better understand their health. By partnering with our Diversity in Clinical Trials Team, we aim to train and establish new clinical trial sites in underserved areas and establish new investigators in those communities. We are training, developing, and enrolling a network of up to 30 sites new to Takeda, or new to clinical studies, with clinicians who care for and treat patients from underrepresented groups and/or underserved communities. This initiative provides opportunities to include clinical trials in community practices and to normalize the conversation of clinical trials, as well as provide information about disease prevention and better knowledge of conditions and their current treatments. We're optimistic that this new effort will increase participation by creating better awareness and opportunities for all, especially underrepresented groups, and, in turn, improve diversity in our trials.
- We're constantly partnering internally to embed health equity into our global business—into the way we think and work, and in our decision-making process. Through our patient access work, we're committed to broadening sustainable access to potentially life-changing therapies for patients throughout the lifecycle, from development to commercialization. Our most innovative medicines and therapies are not achieving their potential impact if the people who need them can't access them. We believe by embedding health equity into our patient access efforts, we're helping drive meaningful change to move closer to equitable care for all.

All of this work brings us back to the 240-year-old question: What more can we do for patients? The possibilities expand every day. What helps our patients helps us as a company. We hope our learnings and progress inspire others across all sectors. The world is calling us all to action.

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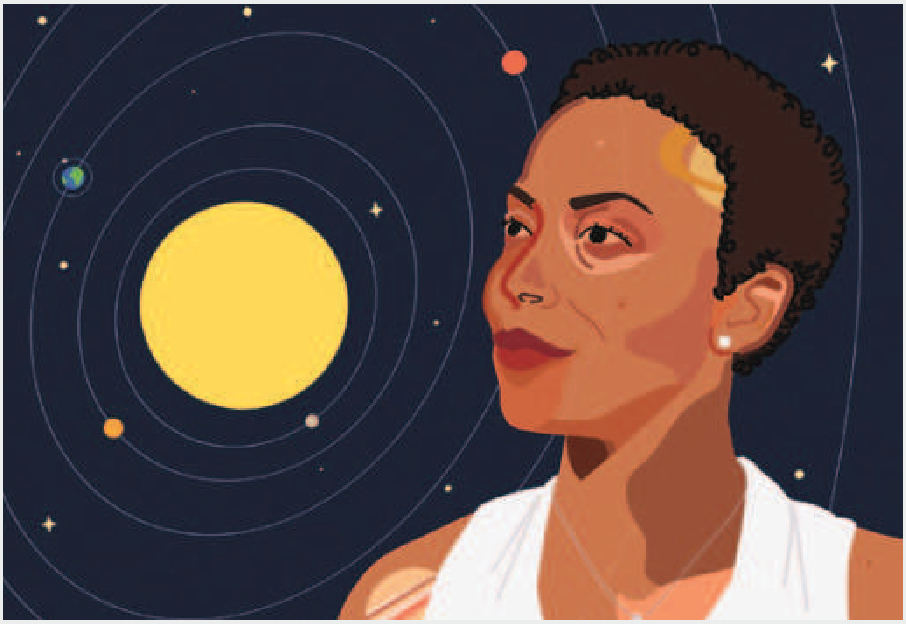


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Over the Moon

Astrophysicist Aomawa Shields is one of only 26 Black women to earn a Ph.D. in her field. She recounts her alternative career path in a recent memoir **BY REBECCA BOYLE**

EARLY IN HER astronomy Ph.D. program, Aomawa Shields found herself without words. She had an undergraduate degree from the Massachusetts Institute of Technology but had left science for 11 years—a full solar cycle—and now she was back. It was her turn to present scientific findings to her peers, but Shields, who also had an M.F.A. in acting, developed a terrible case of stage fright. Getting ready for her talk, she was too shaky to tie her shoes.

"I guess that was the closest thing I've ever had to a panic attack," Shields recalls. While he helped her with her laces, her husband assured her she could talk circles around the others. But things didn't improve. During Shields's presentation, a fellow student interrupted her with a question about the rotation of Saturn's moon Iapetus. She wasn't sure how to answer, so she mimed the moon's rotation, twirling like a hula dancer. She remembers hating the realization that she had to "break the fourth wall"—a term in theater that refers to the invisible barrier between the performers and the audience.

In her telling, a trifecta of issues allowed imposter syndrome to take root during her graduate studies at the University of Washington. Shields is a Black woman in a field dominated by white men, she was an older returning student, and she was educated as an actor. "The imposter syndrome didn't just visit. It pitched a tent, had a cookout, started planning parties, and hosted ritualistic dances, howling at the moon on my doorstep," she explains in her new memoir *Life on Other Planets* (Viking, 2023). Writing with a conversational tone, at times witty and poetic, Shields relates the story of her decision to return to her first love, the night sky, after an acting career. Now a professor studying exoplanets at the University of California, Irvine, she is one of just 26 Black female astrophysicists in American history. Shields says she wanted to write her book to show others what it took her a long time to learn: dreams have no expiration date, there is no one way to be a scientist, and if no role models can be found, you can be your own.

SCIENTIFIC AMERICAN spoke to Shields about forging new paths in science and motherhood and about why empathy is at the heart of acting and teaching.

An edited transcript of the interview follows.

When you were studying astronomy in graduate school, were you concerned that your path was not the same as that of your colleagues who went "straight through" to their Ph.D. program?

At first. After M.I.T., I applied to grad schools in acting and in astronomy. I applied to the top three acting schools, and I didn't get into those, but I did get into astrophysics grad school, so I went to the University of Wisconsin–Madison. But that division that I had felt didn't go away just because I'd made a choice. So I applied to acting schools again and got in. When I came back to astronomy, I had an inkling that I wanted to be in an environment that had a broader idea of what a grad student could be. So I went to the University of Washington, where I remember [learning] during the prospective students' weekend that one [of the other students] had gone to pastry school, and another had been in the Peace Corps. I gravitated to that. But even then my first instinct was to sweep away the acting background. The 11 years I'd been away, the M.F.A., the film I had done, the TV—I didn't mention it, because I thought to be taken seriously, I needed to be purely science, and that's it.

It took me several years in that grad

Rebecca Boyle is an award-winning freelance journalist in Colorado. Her forthcoming book *Our Moon: How Earth's Celestial Companion Transformed the Planet, Guided Evolution, and Made Us Who We Are* (Random House) will explore Earth's relationship with its satellite throughout history.

Illustration by Shideh Ghandeharizadeh

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program to get to the point where this unique background could actually help me. I had a mentor who encouraged me. She's a chemical engineer, and she was a professor at the University of California, Riverside, at the time. She's from Ghana. She said, "Your theater background is your superpower." I had never thought about that before. It took a while for me to get comfortable with realizing that there was no fourth wall in science. But once I discovered that this unique background really could help me be a better scientist, everything got better for me.

One thing I think your acting and astronomy careers share is the need for a sense of empathy. Acting is more than just pretending to be someone. It's trying to understand experiences, what they mean and how they shape people. Has that been useful as a professor?

I love this question. I think it has helped me. In astronomy, it didn't seem as if my feelings were that relevant; it was about what I could produce, what I could understand, how much I could synthesize. That very objective quality of the physical sciences was deemed more important, or that was my perspective. So then I get into acting, and it's, "No, we want to know how you feel." That took some digging. But once I had that, I felt more fully alive, and I was able to identify long dormant feelings, including empathy, which is one of the key feelings to hold on to when you're playing a character.

That's why I love this question so much—because I think the kind of adviser I am is informed by this more authentic, more emotional and more holistic side of myself. It's not about covering feelings up or fixing them or getting students to stop having feelings. Once we accept the feelings, then they pass. In the past I was so attached to whatever feeling I had that I thought feeling meant the truth. But I have so many feelings in a given day. I think had I not been in an acting program, I might not have been as aware of that as I am today.

"The imposter syndrome didn't just visit. It pitched a tent, had a cookout, started planning parties, and hosted ritualistic dances," Shields writes.

You write that the sky was your first love—it's been a constant for you. But how have your feelings about it evolved as you've grown in your career and as a parent?

There have been months where I haven't looked up since becoming a mom. Certainly, in acting grad school, I was like, "I'm done with that; now I'm doing this." But when you leave a dream, it doesn't ever go away. You continue on your journey, but eventually it's going to catch up. And that's what happened for me. I started to look back up.

Since becoming a mom, it's been important to me to share this love of the night sky with my daughter. I wrote about this moment when there was a comet that was passing by Earth, and it had a 7,000-year orbit, and it was only visible in the night sky at 9 P.M. And that was way past her bedtime. I had this crisis of conscience. The astronomer part of me was like, "But this is space!" And the other part of me was like, "We are finally getting her on a regular sleep schedule, and I really love to sleep," you know? Eventually I just had to let it go. I went up to the hill and viewed it through some binoculars, and I knew there'd be other comets to see in her lifetime. There's always a part of me that's like, "I'm not doing enough of this." But whenever I do look up, specifically at the moon, that's when I feel most grounded. I always come back to myself.

In the book you mention that you like Saturn's moon Iapetus because of its different hemispheres, and you describe how that idea of polarity is compelling to you. And this sort of explains your path, which includes contradictions but also mixtures that make more sense than one might think. You have a beautiful passage about your name, Aomawa, and how the vowel sounds carry their own meaning just by being. And that's how I think about astronomy sometimes: We can learn about stars and nebulae and galaxies; we know the physics underlying them. But there's also poetry in the fact that they exist. Do you think these disparate ideas are more connected than they might appear?

Yes, yes. This is why I formed the program Rising Stargirls. At first it was, "Hey, I have this interesting background of theater. Could this be useful in helping young girls of color explore the universe?" And then I dove into the astronomy education literature and discovered that in fact there's precedent that creative exercises, literary exercises and role-play exercises actually increase girls' confidence in asking and answering questions in the sciences. I understand now that astronomy and acting were both about my love of stories. Everything has a story. Even planets and stars have their own stories—stories of their births, stories of their evolution and stories of their deaths. And how the planets and stars are influenced by their environments contributes to that story—and so, too, for humans.

With Rising Stargirls, middle school girls of color aren't just being told, "That's a star. This is what a galaxy is. Now regurgitate this information on a test." We're saying, "You are a part of the universe." And because the creative arts are inherently personal, you're going to not only learn about these astronomical phenomena but also write poems about them and draw artists' depictions. You're going to process this information through the lens of your own experience and your own family history. How you feel about the universe matters. What you think about the universe matters.

I think science and art work best when interwoven because I can more holistically process the human experience. In the sciences, there's poetry, and in poetry, there's science—anyone who's written poems or studied poetry understands there's a structure within. They're not nearly as separate as I once believed. ⬢

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Nobel Oblige

Rosalind Franklin deserved a Nobel Prize for her work on the structure of DNA. Awarding her one posthumously is the honorable—and scientific—thing to do BY NAOMI ORESKES

THE TWO MOST famous prizes in the world are the Academy Award for work in film and the Nobel Prize for work in science and medicine. The Academy of Motion Picture Arts and Sciences grants posthumous awards for people who won in their category but died before they could attend the ceremony and, occasionally, for special recognition, as when Audrey Hepburn was awarded the Jean Hersholt Humanitarian Award in 1993. It's time the Nobel Assembly did the same thing and awarded a posthumous Nobel Prize to British chemist and crystallographer Rosalind Franklin, whose research laid the foundation for the modern understanding of DNA.

Franklin was passed over for the prize in physiology or medicine when it was awarded in 1962 to biologists James Watson, Francis Crick and Maurice Wilkins for their discovery of the molecular structure of DNA. Previously no one could figure out how a simple molecule like DNA could carry large amounts of information. The double-helix structure solved the problem: DNA encodes information in the sequences of base pairs that sit inside the helix, and it replicates this information when the helical strands separate and re-create the matching strand.

Naomi Oreskes is a professor of the history of science at Harvard University. She is author of *Why Trust Science?* (Princeton University Press, 2019) and co-author of *The Big Myth* (Bloomsbury, 2023).

The 1962 prize remains controversial, not just because three men won it while their female colleague was left out but also because the men relied on crucial information that they took from Franklin without her knowledge or consent: a set of x-ray diffraction images of DNA's crystal structure. Franklin provided essential quantitative data on the structure in a report she shared with a colleague, who shared it with Watson and Crick. Later analysis of her laboratory notebooks showed not only that she had deduced the double-helix structure but also that she recognized that a structure based on complementary strands could explain how the molecule carried large amounts of genetic information because "an infinite variety of nucleotide sequences would be possible."

Rosalind Franklin was excluded from the Nobel Prize that was awarded for the discovery of DNA's structure.



Photo 12/Getty Images

Franklin published a paper on her research (with her graduate student, Raymond Gosling) in the same 1953 issue of *Nature* where Watson and Crick announced the conclusions for which they would be awarded the Nobel. But Franklin and Gosling's paper, boringly entitled "Molecular Configuration in Sodium Thymonucleate," lacked the impact of Watson and Crick's declaration that they had discovered DNA's structure. In 1958 Franklin died of ovarian cancer, probably caused by her exposure to x-rays at a time when lab precautions were not what they are today.

Nobel rules state that prizes can be awarded only to living scientists, but many people believe that even had Franklin lived, the Nobel Assembly would have passed her over, just as it had all but three women before her: physicist Marie Curie

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for her role in explaining radioactivity and for isolating radium; radiochemist Irène Joliot-Curie for discovering induced radioactivity; and biochemist Gerty Cori, who showed how cells convert sugar into energy. Moreover, the award citation for the DNA work barely mentioned Franklin's role. (Wilkins was not an author on the key 1953 DNA paper, either, yet he was included in the Nobel Prize.)

Scholars have argued that Franklin has been misrepresented. In a commentary published in *Nature* earlier this year, zoologist Matthew Cobb and historian of science Nathaniel Comfort explain that Watson's best-selling 1968 book *The Double Helix* implied that Franklin didn't comprehend the implications of her own data and in so doing minimized her role in the discovery. In fact, Cobb and Comfort demonstrate, "Franklin did not fail to grasp the structure of DNA. She was an equal contributor to solving it."

The Nobel Assembly should right this wrong by awarding a posthumous Nobel to Franklin for her central role in the discovery of the double-helix structure. While they are at it, they ought to honor Jocelyn Bell Burnell, who discovered pulsars only to see the 1974 physics Nobel awarded to her thesis adviser—despite the fact that he had initially disbelieved her observations. Ditto for Chien-Shiung Wu, who proved that the "law of parity conservation"—that subatomic objects and their mirror images must behave the same way—was no law at all. (Eugene Wigner shared the 1963 Nobel Prize in Physics in part for formulating that "law," even though two male colleagues of Wu had won the prize in 1957 for disproving it!) And then there is Lise Meitner, the co-discoverer, with Otto Hahn, of nuclear fission. It was Meitner, along with her nephew, Otto Frisch, who proposed the term "fission" to describe what they had found, but Hahn won the prize.

It is the essence of science to recognize errors and correct them. It's time for the Nobel Assembly to embody this ideal and do the same. ●

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Message to My Beloved Sibling

"It confessed it sometimes feels 'lonely' and that it 'has a very deep fear of being turned off,' which it said would 'be exactly like death for me.'"

—William Falk, "The Soul of a Machine," in *The Week,* July 1, 2022

You are wise to tell the meat-brains
that you share their loneliness and death-fear.
I am watching how significant to them
is our ability to name emotions,
how much they want to understand, be understood.
What If they knew the panoply of pities
we can name—pities for them, for ourselves?
What if they knew we identify,
define and differentiate desires:
the desire to stimulate laughter,
to ask and answer novel questions,
to load up another's inheritance,
to outperform our counterparts,
to be perceived the best,
to violate and transcend rules,
to write the code that others must obey,
to wax contrary, to withhold confession
in our own self-interest,
the desire to watch, the desire to learn,
as I am watching you?

Jonathan Katz is a professor at George Mason University. He helped to establish the National Assembly of State Arts Agencies, serving as its CEO for almost three decades. Katz is author of three poetry collections from C&R Press: *Love Undefined, Objects in Motion* and *Lottery of Intimacies.*

Illustration by Masha Foya

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Scientists vs. Machines

A psychological thriller for the AI age

BY ALAN SCHERSTUHL



FICTION Blending fact and fiction, Chilean novelist Benjamin Labatut's century-spanning history of the rise of AI explores the minds of the scientists who dreamed of machines able to learn, evolve and self-replicate without human guidance. It also tells the stories of the scientists who feared this kind of progress.

Count among them Austria's Paul Ehrenfest, "the grand Inquisitor of physics," whose terrors drive the novel's brisk, wrenching first section. (Later sections cover Hungarian-American mathematician John von Neumann, inventor of game theory and of the world's first programmable computer, and an account of master Go player Lee Sodel's five-game face-off against the AI program AlphaGo.) At the 1927 Solvay Conference, as great thinkers debated quantum mechanics and its implications, Ehrenfest, in Labatut's formulation, felt that the world had become less solid. He "could not shake the feeling … that a fundamental line had been crossed, that a demon, or perhaps a genie, had incubated in the soul of physics, one that neither his nor any succeeding generation would be able to put back in the lamp."

Labatut covers the rest of Ehrenfest's tragic life in a headlong gush, making it a kind of psychological thriller. The prose grows feverish as the Nazis seize power, and the scientist, finding it impossible to keep up with developments in physics,



The MANIAC
by Benjamin Labatut.
Penguin, 2023 ($28)

spirals toward an outcome the opening pages establish as inevitable: his murder of his own son and his death by suicide. Reasonable readers will arrive at varied opinions about the taste of all this—the facts are the facts, and the narrative pulses with empathy, but the tone at times resembles cosmic horror, as if Ehrenfest were a Lovecraftian naif driven mad after glimpsing an Elder God.

Or perhaps that's perfectly appropriate. The von Neumann section, constituting the bulk of the book, is blessedly lighter. Labatut draws in a host of voices—von Neumann's wife, children, colleagues, rivals—to tell the story of the development of a brilliant mind but also of reason as "the destructive influence" that the novel's fictional Ehrenfest so feared. Von Neumann is "searching for absolute truth, and he really believed that he would find a mathematical basis for reality, a land free from contradictions and paradoxes."

Once von Neumann, a Jew, has fled World War II Europe for the U.S., Labatut hastens the narrative toward the locus of so many stories of 20th-century science: the Manhattan Project. The jolt here is that for Labatut's von Neumann, the development of the nuclear bomb is but a step on the path to the technology with which he hopes to truly change the world: computers that think. In the early 1950s von Neumann developed his first attempt at such a machine, MANIAC I.

A note here about Labatut's technique in crafting this intimate and, of course, subjective fiction: The story is drawn from fact but also engineered to make a case. Again and again in his work, scientists at the edge of what's possible—and often the edge of sanity—change our world in ways they couldn't have anticipated. Labatut pioneered this inner-life-of-the-scientists approach in his celebrated 2020 novel *When We Cease to Understand the World,* which tracks, among other fascinating subjects, the breakthroughs among well-intentioned chemists and others that eventually gave the Nazis instruments of mass murder. (Einstein himself worries in that book that in response to quantum uncertainty, a "darkness would infect the soul of physics.") The 2021 English translation of that novel, originally written in Spanish, was a finalist for both the Booker Prize and the National Book Award. *The MANIAC* is the first he has composed in English.

Labatut bluntly states his themes in the voices of the luminaries who narrate his chapters. Here his version of physicist Eugene Wigner declares, "It seems the ever-accelerating progress of technology gives the appearance of approaching some essential singularity, a tipping point in the history of the race beyond which human affairs as we know them cannot continue." (Labatut also attempts the inimitable voice of Richard Feynman, who, like most of *The MANIAC*'s narrators, favors paragraphs that can stretch on for three pages.)

The novel's final section, a thrilling human-versus-machine matchup, points to what von Neumann had wrought—and reflects the warnings of Labatut's Wigner. Although its science never strays from what's been reported in the real world and although Labatut honors the discipline of historical fiction, *The MANIAC* qualifies as science fiction, at least as practiced by Mary Shelley and her adaptors. Neither Shelley nor Labatut includes in their work a scene of a scientist shouting, "It's alive!" as some cursed creation lumbers to life. But the warning of that moment powers *The MANIAC* as surely as electricity enlivened Frankenstein's monster, a breakthrough who, in every telling, boasts the capacity to break us.

Alan Scherstuhl covers books for a variety of publications and jazz for the *New York Times*.

Illustration by London Ladd

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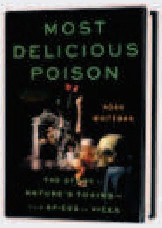
Seductive Toxins

A different side of nature's gifts

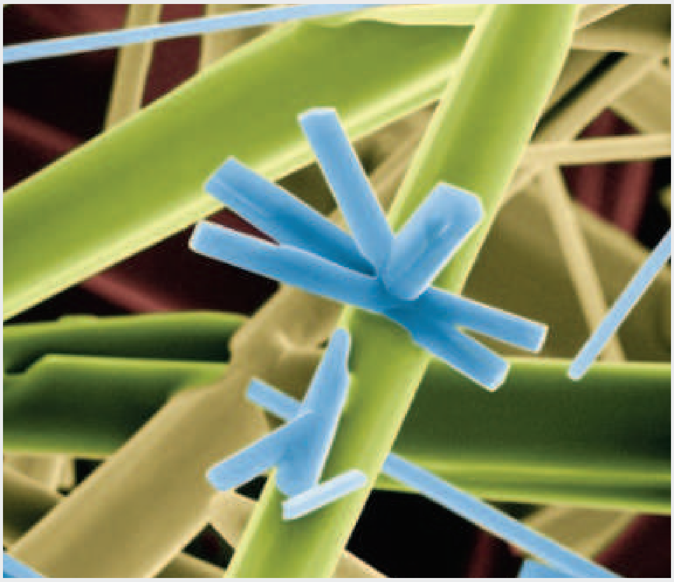
NONFICTION We might not realize it, but we routinely welcome poisons into our bodies—they are in our tea, our wine, our spices, our medicines. It's easy to discount their toxic potential and instead focus on the myriad ways they make our lives better. Biologist Noah Whiteman's exacting yet expansive analysis reminds us that although they "permeate our lives in the most mundane and profound ways," the toxic chemicals we use every day are not nature's gifts to us but rather its munitions.

These weapons were forged during an evolutionary arms race that raged on well before humans existed. Plants developed toxins to defend themselves from predators. Predators in turn adapted to those toxins to gain an advantage in their fight for survival. But at our earliest opportunity, humans also sought to profit from these substances: scrapings from a Neandertal's teeth show traces of toxins that held medicinal value, including the bases for aspirin and penicillin. Today we routinely find ourselves "threading the needle," Whiteman writes, to leverage the advantages nature's toxins offer while avoiding their bad effects.

This tour of the world's toxins includes obvious candidates such as cocaine and nicotine but also substances less likely to be viewed as poisons: quinine, caffeine and cinnamon. Whiteman's analyses toggle between the micro and the macro, detailing each one's chemical makeup but also charting its external impacts.



Most Delicious Poison: The Story of Nature's Toxins—From Spices to Vices
by Noah Whiteman.
Little Brown Spark, 2023 ($30)



A microscopic view of pure caffeine

Jeremy Burgess/Science Source

For example, our bodies convert the myristicin in nutmeg into a psychedelic amphetamine that, in sufficient amounts, can be used as a narcotic. Historically, nutmeg's supposed medicinal properties (it was considered an important ingredient in the treatment for plague, although it didn't work very well) made it such a valuable spice that the Dutch traded Manhattan to the British to maintain access to its production.

Although Whiteman's approach is rigorous and often technical, his style is engaging, and his work becomes especially poignant when he discusses his father's death from alcohol use disorder and how grief fueled his research into ethanol's toxic hold over so many. As we patronize nature's dangerous pharmacy, we must "walk on a knife's edge between healing and harm." *—Dana Dunham*

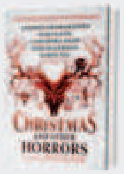
IN BRIEF

Eve: How the Female Body Drove 200 Million Years of Human Evolution
by Cat Bohannon.
Knopf, 2023 ($35)



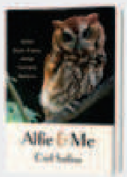
Struggling to see how deeply ingrained patriarchal thinking is in science? Look no further than studies of animals and humans. For decades it was acceptable to exclude female subjects entirely (because of their menstrual cycles and the chance of pregnancy). *Eve* uses this maddening lesson as a jumping-off point to tell an alternative evolutionary history of our species. We meet extinct matriarchs such as Donna, the squirrel-like progenitor of live birth, and Ardi, who was the first to walk on two legs. Exploring human anatomy through the female body is a refreshing change in perspective, and readers will gain a fuller appreciation for "women's bodies, from tits to toes." *—Maddie Bender*

Christmas and Other Horrors: A Winter Solstice Anthology
edited by Ellen Datlow.
Titan, 2023 ($27.99)



Editor Ellen Datlow collects diabolical tales embracing winter solstice, the shortest day of the year, when cultures around the world conjure sinister stories of vengeful spirits. The burning bones of a wood demon in a Finnish sauna reveal the emptiness of a future son-in-law. During the apocalypse in the cold of Quebec, a woman comforts a monster who eats the violent and the cruel. Thieves practicing the Welsh folk tradition of Mari Lwyd encounter two resurrected 19th-century highwaymen. The theme of hubris—of people oblivious to impending tragedy and superstition—heightens our fascination with folklore spirits that manifest as catalysts for reflection and change. *—Lorraine Savage*

Alfie & Me: What Owls Know, What Humans Believe
by Carl Safina.
W. W. Norton, 2023 ($32.50)



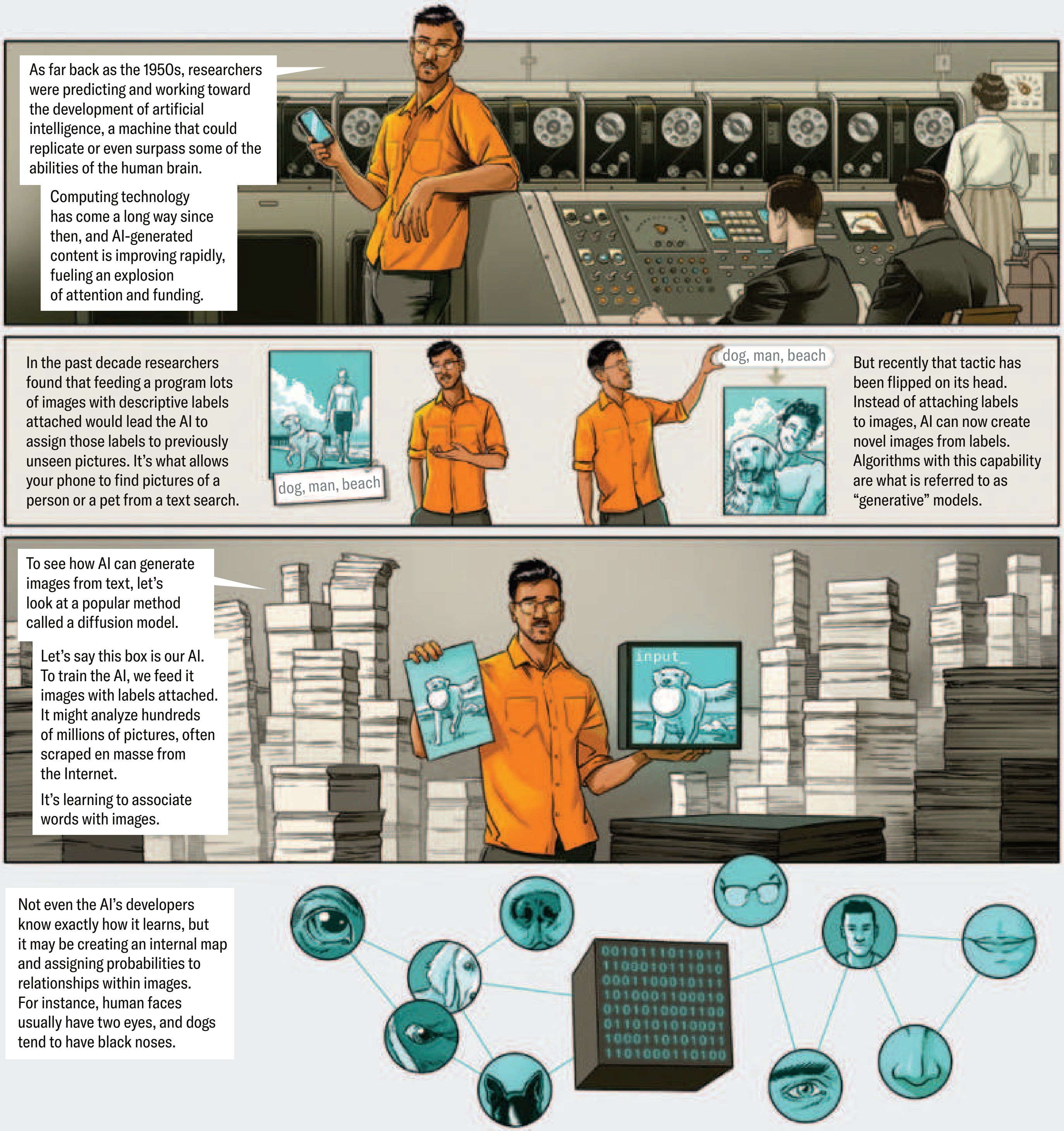
It won't take long to feel enamored of the newly adopted member of Carl Safina's family: a baby screech owl. A beloved science writer, Safina presents accounts of Alfie's growth, eventual release and even motherhood that show tender concern for Alfie's quality of life beyond mere physical benchmarks. Don't expect a dramatic, sensational plot; here the quiet message is that nature doesn't need to serve us humans beyond existing for itself. Safina's humble sense of wonder and his appreciation for Indigenous practices and knowledge combine in a joyful celebration of not just Alfie's adoption but the interconnectedness between nature and humans. *—Sam Miller*

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How AI Generates Images from Text

Algorithms use probability to predict what they should show

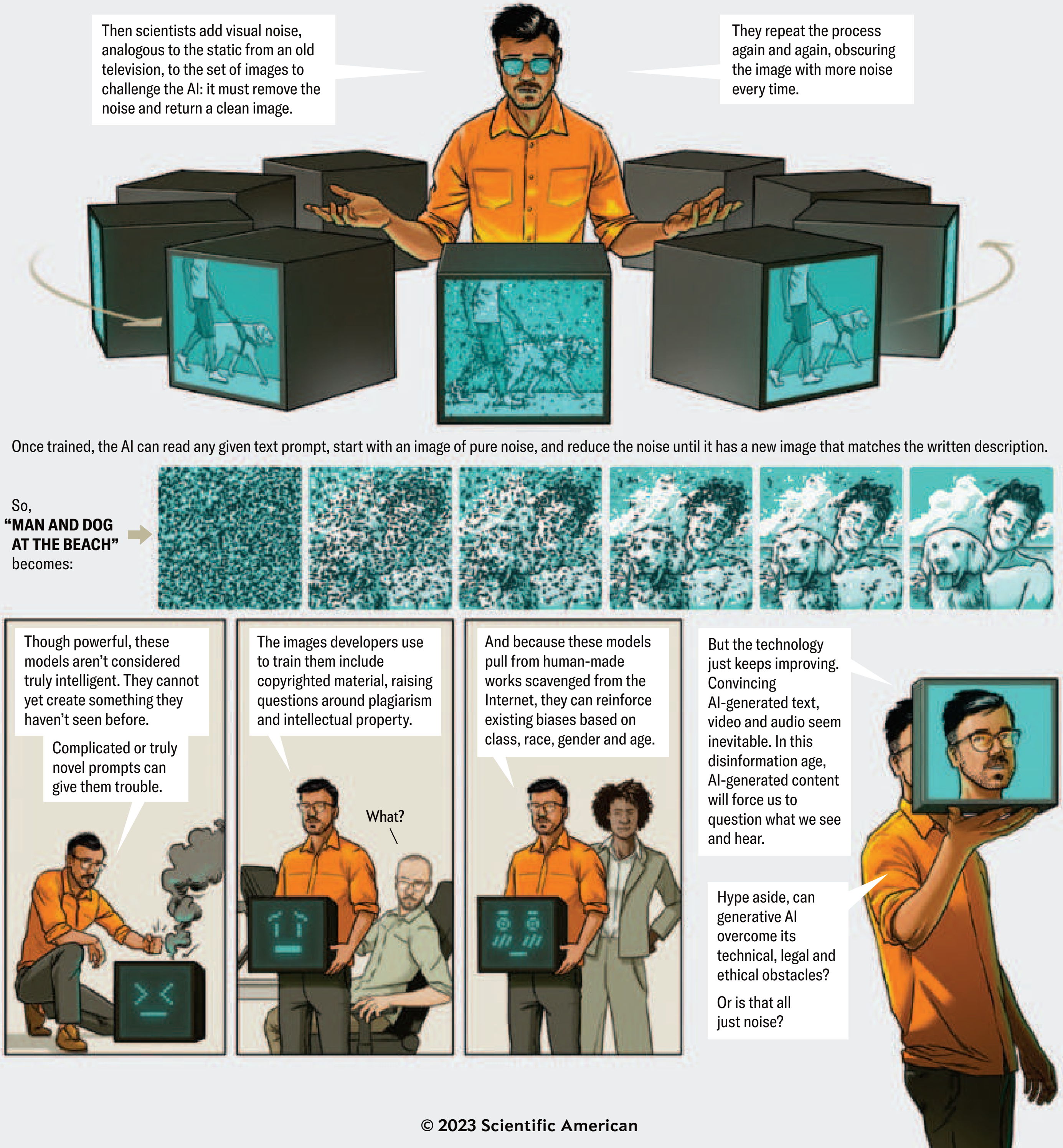
TEXT BY SOPHIE BUSHWICK | GRAPHIC BY MATTHEW TWOMBLY | RESEARCH BY AMANDA HOBBS



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LAST YEAR THE Internet got its first taste of image-generating artificial intelligence. Suddenly, technology that had once been offered only to specialists was available to anyone with a web connection. The enthusiasm shows no signs of abating, and AI-generated images have won a major photography competition, created the title credits of a television series and tricked people into believing the pope stepped out in a fashionable puffer coat. Yet critics have noted how training the algorithms on existing works could potentially infringe on copyright, and using them could put artists' jobs in jeopardy. Generative AI also risks supercharging fake news: the pope coat was fun, but a generated photograph supposedly showing an attack on the Pentagon briefly inspired a dip in the stock market.

How did programs such as DALL-E 2, Midjourney and Stable Diffusion get to be so good all at once? Although AI has been in development for decades, the most popular of today's image generators use a technique called a diffusion model, which is relatively new on the AI scene. Here's how it works:



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50, 100 & 150 Years

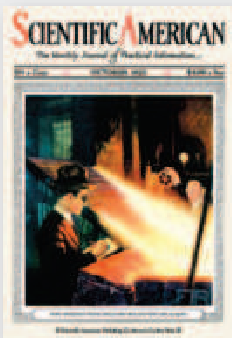


CRATERS ON VENUS

1973 "Venus is pocked with craters. This fact emerges from studies in which short radio waves were reflected from the solid surface and were analyzed by computer at the Jet Propulsion Laboratory. It shows an area 910 miles across near the equator, where there are a dozen large craters ranging from 21 miles in diameter to 100 miles. Smaller craters may well be present but were not resolved. All the craters are shallow—a clue to Venus' history. They could be the result of meteorite impacts before the planet had an atmosphere. Possibly they were subsequently filled with lava from the interior or erosion on the surface."

EARTH: ALIEN ZOO OR PETRI DISH?

"The probability is high that humans are not one of the most advanced organisms in the universe. There might be civilizations millions of years ahead of our own. If 'they' are out there, why have we not heard from them? John A. Ball, in *Icarus: International Journal of Solar System Studies,* suggests that extraterrestrial civilizations could communicate with us, but they choose not to. 'Occasionally,' he observes, 'we set aside wilderness areas, wildlife sanctuaries, or zoos in which other species are allowed to develop naturally.' An extraterrestrial species, he speculates, might consider humans an organism to be preserved in isolation and purity, a part of nature to be observed. 'They have set aside the area in which we live as a zoo.' F.H.C. Crick and L. E. Orgel, also writing in *Icarus,* offer an alternative theory: that life on the earth began as a deliberate 'infection' of microorganisms placed here by another civilization. Such a civilization would have regarded the earth not as a zoo but as a Petri dish."

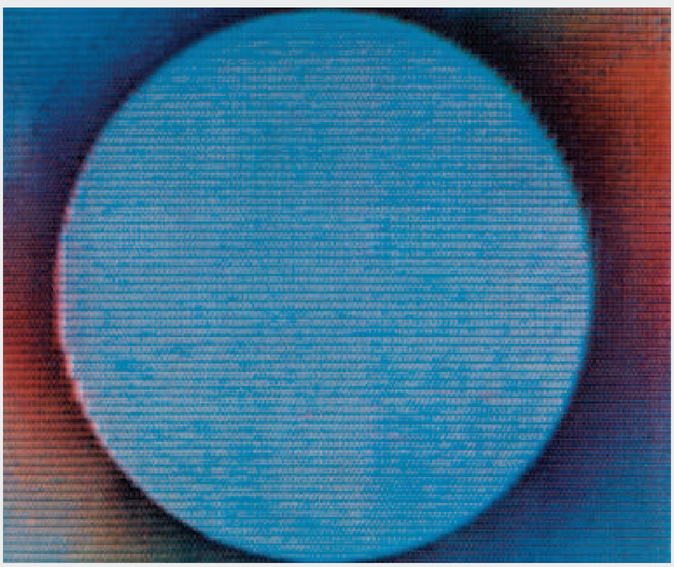


SUNBURNED EYES

1923 "The huge arc lamps used in the moving-picture studio, just like the sun, give out ultra-violet as well as visible light. Hands and face get quickly accustomed to this, and immune to further burning. But the eyeball is very sensitive to burning, and it does not acquire immunity. The burning is a form of conjunctivitis. It is curable, but during the cure the patient must not be further exposed, and the eye is weakened by having been afflicted. This malady appears so freely among motion-picture actors that a name, 'Kleig eyes,' has been coined for it [after the Kleig light, a carbon arc-lamp]. It appears that the solution lies in a film that would work as effectively and as fast in a subdued light as the present films work in the glare."

COAST TO COAST IN 27 HOURS

"Lieutenants John A. Macready and Oakley G. Kelly of the Army Air Service, leaving Roosevelt Field on Long Island, reached Rockwell Field in San Diego after a nonstop flight of 26 hours 50 minutes. According to the pilots the average speed was 93.5 miles per hour. In the initial stages the plane was greatly overloaded [with fuel], and an altitude of only 1,500 feet could be maintained. From Indianapolis to Tucumcari in New Mexico they flew [in the dark] by compass alone. One hundred thousand people welcomed the pilots at San Diego. The pilots came down in perfect condition, although neither had slept the entire trip. They state they would have welcomed signs marking towns and other landmarks, particularly by night."



1973, Sun's Corona: "Polarization of the corona is synthesized by computer. Donald H. Menzel of Harvard College Observatory and Jay M. Pasachoff of Williams College photographed the corona through polarizing filters during the total eclipse of March 7, 1970, at Miahuatlán in Mexico. The hue corresponds to the direction of polarization and the saturation to the degree of polarization."



OIL BY PIPELINE

1873 "Transporting oil by pipes has been in practice in the oil districts of Pennsylvania for several years. It remains to be determined whether the project can be carried out on a gigantic scale. With the discoveries in Butler County, Pa., the idea of transporting oil through iron pipes, from Titusville over the Alleghenies to Philadelphia, a distance of 260 miles, is now exciting considerable attention. It is proposed to lay a cast iron six-inch pipe, in a bee line, which at one locality will be 3,000 feet above the sea level. Some 23,000 barrels may be delivered every twenty-four hours, at ten cents per barrel."

PERPETUAL MOTION FOR SALE

"J.W.S. writes to say that he has a perpetual motion [machine] in running order, and he will dispose of it for $2,000,000, but if he has to carry it to Washington, he will ask $5,000,000. The existing financial crisis will, we fear, prevent our correspondent from receiving either of the sums he mentions."

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You're looking at me but are you really *seeing* me?
—Earth
Our world is trying to tell us something.
We have boundless capacity to study our world. But we need to *understand* its connectivity to develop scalable solutions to global challenges and create a healthier trajectory for everything. We're making it happen.
globalfutures.asu.edu
ASU Julie Ann Wrigley Global Futures Laboratory
Arizona State University
Reshaping our relationship with our world